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Strategic Petroleum Reserve (SPR)
Additional Geologic Site Characterization Studies
Bryan Mound Salt Dome, Texas

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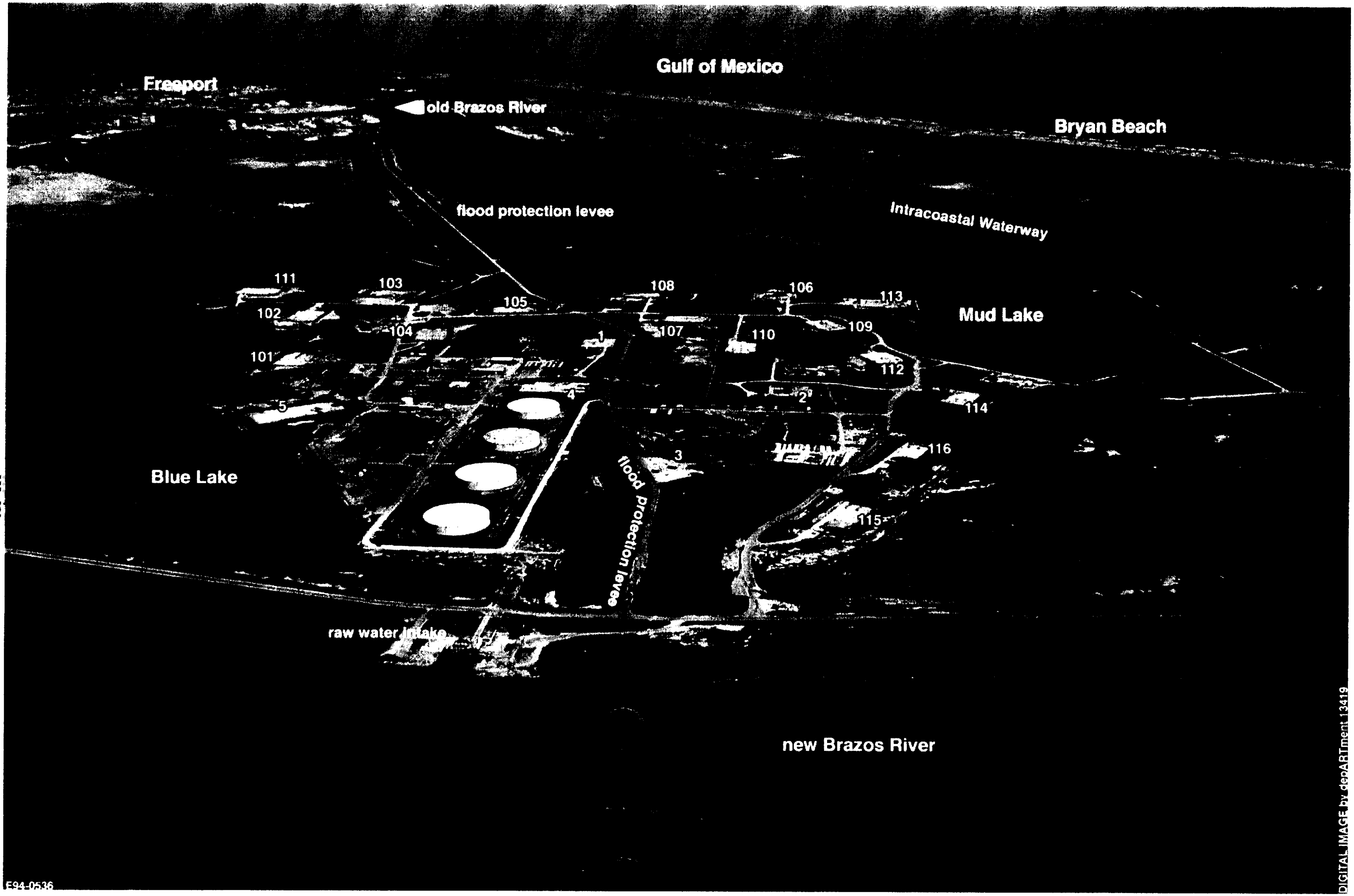
ABSTRACT

This report revises and updates the original geologic site characterization report that was published in 1980. Some of the topics covered in the earlier report were provisional and it is now practicable to reexamine them some 15 years later, using new or revised geotechnical data and that obtained from SPR cavern operations, which involves 16 new caverns.

Revised structure maps and sections show interpretative differences as compared with the 1980 report and more definition in the dome shape and caprock structural contours, especially a major southeast-northwest trending anomalous zone. The original interpretation was of westward tilt of the dome, but this revision shows a tilt to the southeast, consistent with other gravity and seismic data. This interpretation refines the evaluation of additional cavern space, by adding more salt buffer and allowing several more caverns. Additional storage space is constrained on this nearly full dome because of low-lying peripheral wetlands, but 60 MMBBL or more of additional volume could be gained in six or more new caverns.

Subsidence values at Bryan Mound are among the lowest in the SPR system, averaging about 11 mm/yr (0.4 in/yr), but measurement and interpretation issues persist, as observed values are about the same as survey measurement accuracy. Periodic, temporary flooding is a continuing threat because of the coastal proximity and because peripheral portions of the site are at elevations less than 15 A. This threat may increase slightly as future subsidence lowers the surface, but the amount is apt to be small. Caprock integrity may be affected by structural features, especially the faulting associated with anomalous zones. Injection wells have not been used extensively at Bryan Mound, but could be a practicable solution to future brine disposal needs.

Environmental issues center on the areas of low elevation that are below 15 feet above mean sea level: the coastal proximity and lowland environment combined with the potential for flooding create conditions that require continuing surveillance. Prior sulfur mining has resulted in residual high temperature and corrosive groundwater in the caprock and may have contributed to several casing failures. Natural sei,micity has continued as predicted with periodic, minor temblors causing very minor local damage to surface buildings where occurring. Predicted peak horizontal accelerations are sufficiently low so as to cause no damage to mined underground openings such as SPR storage caverns.



Frontpiece Bryan Mound salt dome, Texas, is a topographic high within the coastal marshland, with surrounding lowlands subject to hurricane surge. The principal flood protection levee of the Strategic Petroleum Reserve storage site is shown, along with the diverted new Brazos River and constructed Intracoastal Waterway, all substantial modifications from original conditions. Photo by J. T. Neal, 1992.

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EXECUTIVE SUMMARY

This revision and update to the initial 1980 geological site characterization has relied on some 15 years operating history of the SPR, as well as a more complete understanding of salt dome storage and all that it entails.

The shape of the Bryan Mound salt stock is modified somewhat from the original interpretation, with a very cylindrical overall shape having steep overhangs on the north, east, and south sides and a localized bulge or nose on the east. This revised interpretation allows more buffer space for the existing caverns, or alternatively, the possible expansion space for some 60 MMBBL equivalent cavern volume. However, this additional space is on the present dome periphery, at areas of low elevation and containing Blue and Mud Lakes.

Structural features within the salt stock and external to the dome include at least two intersecting anomalous zones (probable shear zones), dividing the stock into some four individual lobes or spines. These features probably control permeability zones for gas migration within the salt stock, which may be controlling differential intrusion of gas into caverns containing SPR oil. This conceptualization has not been verified, mainly because of the lack of conclusive data.

Salt falls have been a continuing problem within half (ten) of the SPR caverns, accounting for 3 1 of 37 incidents of lost casing. The exact nature of these occurrences is obscure, largely because of the lack of conclusive evidence. No geological correlations have been adequately explained, even though there appears to be a localized clustering of occurrences in half of the total caverns.

Subsidence is the lowest of all the SPR sites, even though the total cavern volume is nearly the same as West Hackberry with a rate nearly six times larger. The explanation lies in much lower laboratory salt creep rates, slightly shallower caverns, and possibly a smaller salt stock which effectively may restrain large scale dome deformations, including subsidence.

Flooding and seismicity risks are very low and are unchanged, but the validation of these potential threats is better established. The overall appraisal for safe storage at Bryan Mound has not been altered; however, confidence in the geologic interpretation is substantially increased.

1 INTRODUCTION AND PURPOSE

Bryan Mound contains the most oil storage volume of the SPR sites, with a capacity of 226 million barrels contained in sixteen new caverns and four caverns acquired from the former owner, of which Cavern 5 is the largest in the SPR system. The Bryan Mound dome is much smaller than either the West Hackberry or Weeks Island domes.

The initial geological characterization of the Bryan Mound salt dome was conducted by D'Appolonia Consulting Engineers, Inc. in 1979-80 [Hogan et al., 19801. Refinements to the original report are now possible, because of new information gained in the intervening years, and because of some thirteen years operating history by SPR. This report thus provides an update of data gathered and a rethinking of the previous geotechnical interpretations.

The regional geologic interpretation has changed relatively little, but new geologic understanding of salt tectonics is revolutionizing current thinking, including exploration for oil in the Gulf of Mexico Basin. The dome has had relatively meager study over the years because of the virtual lack of oil production; thus the structural control and interpretation (especially the relation of dome shape to geopressure) necessary to develop detailed interpretations of external geometry was constrained. This information is still less than at many domes, including all of the other SPR domes.

Caprock conditions have been a continuing concern because of the relatively small thickness and residual thermal conditions created from sulfur mining sixty some years ago, Caprock faulting such as that occurring at neighboring Stratton Ridge has not been noted at Bryan Mound.

Salt contours have been modified, as the reevaluation of earlier data suggest nuances occur in the overhang geometry. A protective shale sheath, similar to West Hackberry and Weeks Island, has been recognized and mapped. The structural interpretation is modified from that in the 1980 report; the refinements show intricacies that had not been recognized previously. Although the new understanding of salt tectonics in the Gulf of Mexico basin has altered traditional concepts, this probably will have little effect relative to storage applications at Bryan Mound.

Sixteen new SPR caverns have been leached and oil has been infilled; Cavern 3 was plugged and abandoned. Caverns have performed essentially as predicted with respect to maintaining mechanical integrity. However, apparent salt falls have been a recurring problem, with more than 30 incidents of lost casing reported since 1982. Gas-in-oil has become an issue as gas quantities in some caverns are sufficiently high to require degassing prior to shipping.

The generally low elevation off of the center of the dome (under-l 5 R) makes periodic flooding a continuing concern, and subsidence resulting from cavern creep closure an ongoing issue. Some ten years of survey data are evaluated, with a view toward forecasting future trends.

Finally, several environmental conditions are considered. A reassessment of hazards identified in the earlier characterization was conducted; DOE now requires that projects of this size and importance be updated at least every ten years. Hurricane threats are virtually unchanged, and revised FEMA flood maps show few changes that would affect Bryan Mound. Seismicity is also unchanged, but the interpretation of the threat has been revised slightly with the introduction of new data.

2 GEOLOGIC ASPECTS

Numerous refinements in the understanding of Gulf Coast geology have been made in the past 15 years; these are summarized in **Appendix A , Bryan Mound Regional Geologic History,** and mentioned at various places in the text. Signz@~~tly, *SPR storage integrig is not affected other than very indirectly, and then in only minor ways.* **Well control** is tabulated in **Appendix** *C* and depicted on **Figure 1,** which also shows locations of the **Geologic Cross Sections.** Stratigraphic nomenclature and the geologic column are listed at **Table 1.**

2.1 Hydrolow

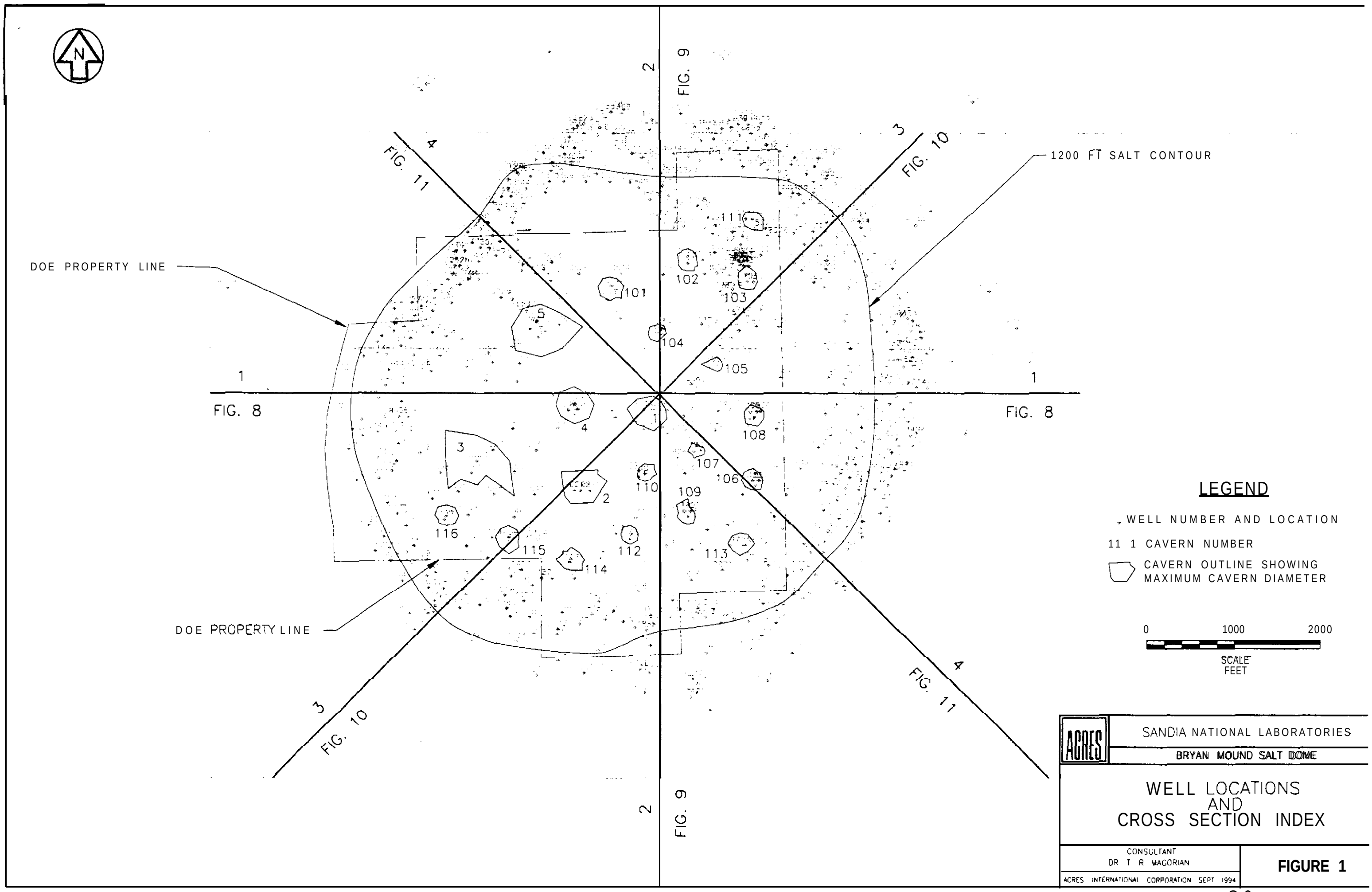
No revisions of significance are required that would change the original 1980 hydrologic characterization, as few new data were obtained, nor did major hydrologic alteration occur during the intervening time.

The **Chicot Aquifer** consists of Pleistocene sands and basal gravel extending over the caprock. The *upper Chicot* consists of shallow fresh water Recent and Wisconsin-equivalent sands of the Brazos Delta down to depths of 270 to 320 feet off the dome to the west.

Table 1 Bryan Mound Stratigraphic Correlation Chart

Unit	Symbol	Litholom
Holocene		alluvium
Pleistocene		
Beaumont		marine clay
Lissie		
Montgomery	**MO**	sand
Bentley	**LS** (lower Lissie)	mud
Lafayette		sand and gravel
Pliocene	**PL**	sand and mud
Miocene	**MI**	
Goliad		sand **(Bigenerina A)**
		shale
		sand (Bigenerina B)
		shale
		sand (Textularia L)
		shale
		sand **(Bigenerina 2)**
		shale
-m-s UNCONFORMITY	**Bigenerina humblei - - -**	UNCONFORMITY
		sand **(Cristellaria I)**
		shale
		sand **(Cibicides opima)**
Lagarto	**AB**	shale
Oakville	**RL**	deltaic sands
Oligocene		
Anahuac	**DR**	shale
Frio	**F**	geopressured shale* and turbidite sand

* **P** on cross-sections **(Figures 8-11)** indicates geopressure, marked by reduced resistivity



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BRYAN MOUND SALT DOME

WELL LOCATIONS
AND
CROSS SECTION INDEX

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FIGURE 1

Only the uppermost of these sands, shallower than 100 ft, is fresh on the top of the dome (with a normal sand resistivity greater than 20 ohm-meters), being presently recharged from the diverted Brazos River. The remaining upper Chicot sands are brackish on the dome and nearby on the flank in its hydrologic shadow eastward and toward the coast. The DOE brine disposal wells and the Greenbrier well encountered freshwater sand to a depth of 260 feet in the upper Chicot. Further east in the Dow plant area, the deepest freshwater sand extends only to a depth of 200 feet, although the rest of the upper Chicot to a depth of 300 feet is only slightly brackish.

The lower *Chicot Aquifer,* including all of the Lissie sands, is brackish throughout the area and the primary source of industrial water. The caprock above the sulfur-producing zone is highly fractured and permeable, and the water is quite saline and corrosive, being fully-saturated at the top of the salt stock.

The caprock drapes over the outer edge of the salt and provides a source of brine flowing into the **Evangeline Aquifer,** the Pliocene sands on the flanks of the dome. Salinity in the Evangeline Aquifer decreases gradually updip, away from the salt stock, outside of the area of this characterization. These beds provide the deeper industrial water supply of the Freeport area; their permeability is discussed in the following section on brine disposal wells.

The deeper surrounding Miocene sediments, occasionally referred to as the **Burkeville Aquifer,** are all salt-saturated near the dome. They underlie the outer edge of the caprock and are in contact with the salt stock.

2.1.1 Injection Wells for Brine Disposal

Pliocene Iniection Zones: The saline zone with the maximum hydraulic transmissivity is the thick sand and gravel at the base of the Pliocene, found at a depth of 1950 R in the original disposal area east of the dome(no longer being used). It is a point-bar gravel, the oldest deposited by the Brazos-Colorado Delta.

Each gravel bar is approximately 100 ft thick, and the normal double ox-bow sequence is overlain by clean reworked sands. A 25-R thick sand with some 10 darcy-feet transmissivity occurs in a middle mud and silt. An upper sand with a lOO-foot point-bar is overlain by a massive 30-foot sand with 70 darcy-feet transmissivity and a clean

20-foot sand at the top. These beds persist in detail around the entire dome.

The total 500-foot interval contains 375 feet of sand and gravel with point (local) permeability as high as 5-6 darcies east of the dome. The total transmissivity observed at the disposal site is on the order of 170 darcy-feet, as estimated from the logs run in 1978 when cores were taken only in the Miocene.

Although the basal Pliocene gravel thins toward the dome, the overlying 350 feet of Pliocene silt, mud and marine Buliminella clay do not, providing a continuous seal for fresh-water aquifer protection. The dip is very gentle and to the east, away from the dome. Near the old Brazos channel, the spreading underground brine flow turns southeast and flows offshore where sand continuity can be demonstrated beyond the Tenneco Block 382s well, an identical section in two Mobil Block 382s gas wells (producing from deeper sands) and on across the wide continental shelf

Miocene Injection Zones: The next-most promising zone is the Goliad sand at a depth of 2650 to 4000 feet: five permeable sands total some 100 darcy-feet of transmissivity. Most of this formation injectivity, some 70 darcy-feet, is in the 2800-feet (depth) sand, apparently a delta-mouth bar, perhaps an early marine expression of the Brazos-Colorado delta. This zone could be completed concurrently with the Pliocene.

The few cores taken in the rest of the Goliad are muddy, marine sands. The first disposal well completed in this zone was a failure, mostly due to the drilling mud used in setting the screen.

The lower Miocene Oakville sands have some 20 darcy-feet of transmissivity between 5300 and 6800 feet depth. They are faulted at least 100 feet in wells 2 and 2B. This may be the fault with 300 feet of cutout in the Dow-Fee well to the northwest. Most of the wells closer to the dome drilled by Freeport-McMoran, Texaco, Exxon, Tenneco, Homestake and their predecessors are faulted, By staying in the Goliad and shallower, above the middle Miocene Lagarto shale which buries these faults, continuous disposal zones can be found and used with minimal pressure build-up.

2.1.2 Overlying Sediments

The sediments overlying the caprock have been included in the Lissie formation which can be divided, for convenience, into an upper Montgomery sand and a lower sand which may be correlated with the Bentley.

The Willis formation is found above the caprock, suggesting that all sediments over the dome are middle Pleistocene and younger.

2.2 Caprock

The simple structure of this dome is shown in the Pleistocene beds above the caprock, mapped at the lower sand level in the Lissie. *The dome is almost circular and unfaulted.*

All of the Freeport sulfur well data has been included in the remapping and interpretation of caprock **(Figure** 2) . The caprock edge merges into the top of the Miocene, the last fully-marine sediments. Since offshore domes have little or no caprock, it thus appears that the caprock at Bryan Mound is Pliocene and younger in age.

2.2.1 Anomalous Zones

The *anomalous zones* (A&) that often occur between major segments in salt stocks, called lobes or spines by various authors [Neal et al., 19931, show as linear depressions, actually grabens, on the caprock upper surface. They are bounded by normal faults which meet at the top of salt. The principal northwest-southeast AZ is apparent on the caprock contours and is congruent with the gravity flexure and external structural features at depth **(Figures 5 and** 7). At least one more AZ almost normal to it appears to be present, segmenting the salt stock into at least four discrete lobes. The north-northeast / south-southwest trending AZ is evidenced by more subtle surface topographic expression, by external structure manifested at depth, and by internal structural features in the salt, as observed on well logs. In salt stocks this large, four or more spines (lobes) are usually present; thus Bryan Mound appears typical. The limited expression of the AZs indicates strong water flow through the caprock, typical of the Brazes deltaic sands which the dome is buried in.

2.3 Salt

2.3.1 Salt Nature and Internal Structure

The dome salt at Bryan Mound contains significantly more shale (and possibly less anhydritic) than at domes further east. This agrees with the known changes in composition across the Coastal Salt Dome Basin, with more shale and sylvite near the western

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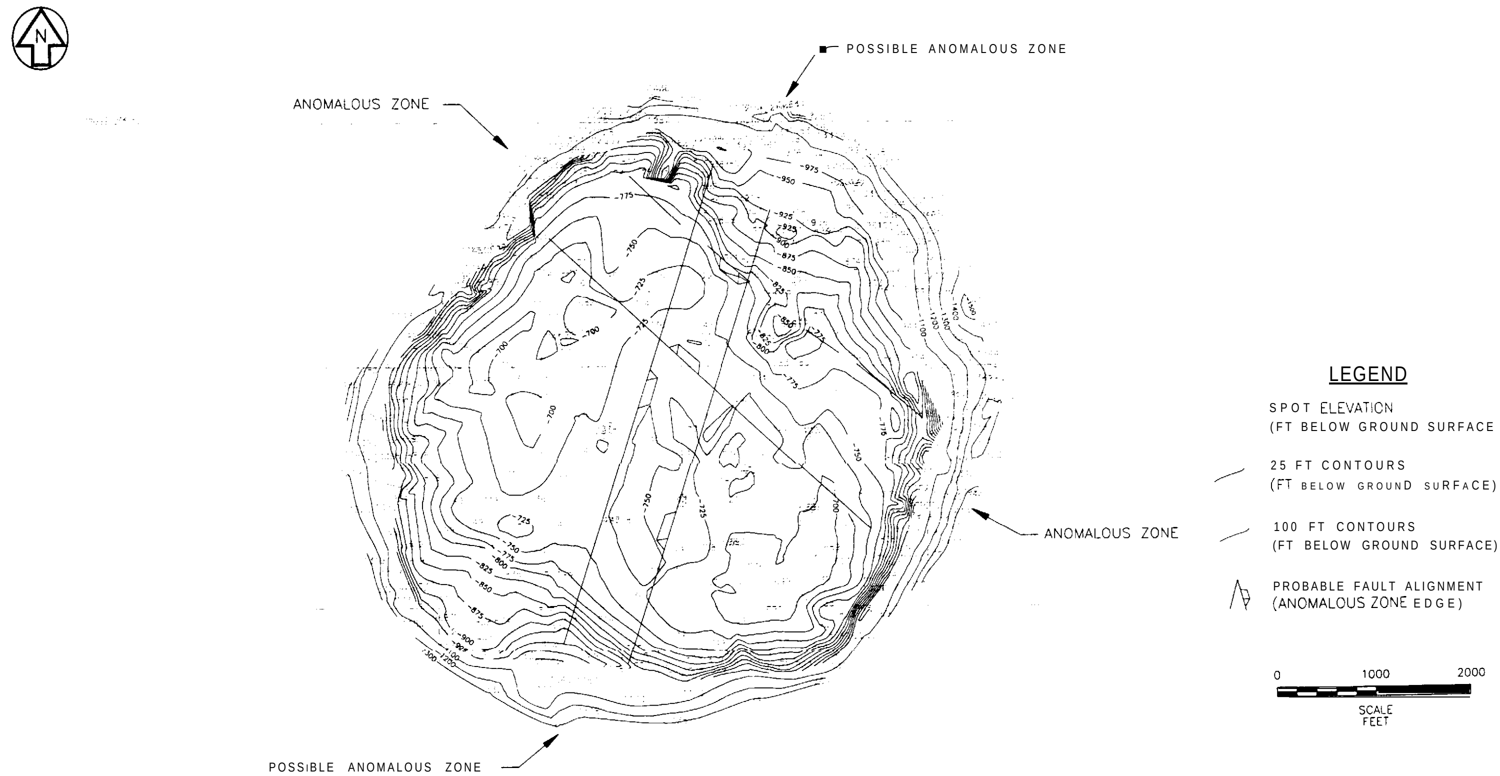
The anhydrite is less abundant than at Big Hill, as indicated by available logs. Most of the anhydrite bands seen on well logs are near vertical and parallel to the edge of the salt stock. Some of these anhydrite bands can be correlated between adjacent wells in a single cavern, but the more extensive mapping and correlation that enabled spine delineation at Big Hill [Magorian et al., 19881 was more difficult at Bryan Mound. A unique opportunity was present to determine internal structure using well log correlations in the six 3-well caverns that were drilled prior to the recognition that such leach configurations could create salt fall problems. Sections of shale or anhydrite layers which can be correlated on all three logs in Caverns IO6 through 110 provide exact dip and strike of the internal structure and salt flow regime, allowing the identification of salt spines as accurately as in a mine **(Figures 3a, b)** The southwest-northeast section (Fig 3a) shows two sylvite bands found only in the southwest corner of the dome dipping outward from the southern spine. Dips on both flanks are seen. The anomalous zone (AZ) described by Thorns [in Neal et al., 19931 is crossed between Caverns 105 and 110. Shale dips to the southwest suggest that this AZ may itself dip southwest. This is the first time that any data on the possible dip of an AZ has been traced on logs. Both flank dips of the northeastern spine are seen.

The southeast-northwest section (Fig. 3b) shows the inner flank of the southern spine and crosses both AZs near their intersection. Only the inner flank of the northeastern spine was logged. The absence of outer spinal dips in this section is another indication of the width of available salt outside the present cavern array.

Neither section or any of the available logs show the western and northernmost spines. In almost all of the other caverns, two wells were drilled, as at Big Hill, showing the general direction of dip of correlative shale and anhydrite layers. The logs are not of sufficient sensitivity in most cases to allow satisfactory correlations, as fairly specific character is required to validate the correlations.



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BRYAN MOUND SALT DOME

CONTOURS
TOP OF CAPROCK

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FIGURE 2

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The character of salt as shown in thin sections includes clear salt with minor anhydrite, the most common secondary component. Black shale is the most common inclusion material. Some of it is slightly radioactive. Some of the less radioactive inclusions were sectioned. They all show highly-organic black shale. This is normal, since in eutrophic sediments, the radioactivity is confined to the inorganic detritus. **APPENDIX D** contains photos of cores and thin sections.

2.3.2 Shape of Salt Stock and Overhang Geometry

Bryan Mound is more cylindrical than many domes **(Figure** 4,4a). This may be due to four almost-equant spines, discussed below under "Salt Stock External Structure," which could have resulted in more uniform diapiric rise in individual segments, and in subsequent erosion. The top of the salt surface is more nearly level than found at most domes; this presumably results from water migration and associated caprock formation processes. The normal vertical shape of the Bryan Mound salt stock is modified in several significant ways. It leans to the southeast at depth, with a bulge on the northeast, an overhang on the south, and possibly other overhangs. In the zone of interest for cavern development from 2000 to 5000 feet, the salt edges are almost vertical like most domes, except near the minor bulge on the east. The overhangs are not believed to create a significant problem for storage, but must be mapped for any future expansion.

The most important difference in this interpretation as compared with the 1980 report [Hogan et al., 19801 is the overall dip of the axis of the dome, and the direction in which it leans. The 1980 interpretation relied on the 1949 refraction survey that indicated major overhangs on the west side, leading the authors to conclude that the salt stock leaned to the west. Additional access to this data along with analysis of the deep well control suggests that the salt stock leans slightly to the southeast, toward the coast. The bulge on the east side of the dome, which extended halfivay around the dome in the 1980 characterization [Hogan et al.], is now believed to be more localized to the area of a few particular wells and adjacent fault block.

This revised interpretation is in agreement with Big Hill and some other domes that lean as much as 30" toward the coast. The Five Island domes, particularly Avery Island and Cote Blanche, however, lean into the Iberia trough. A deep Frio trough east of Stratton Ridge may extend offshore southeast of this dome as well.

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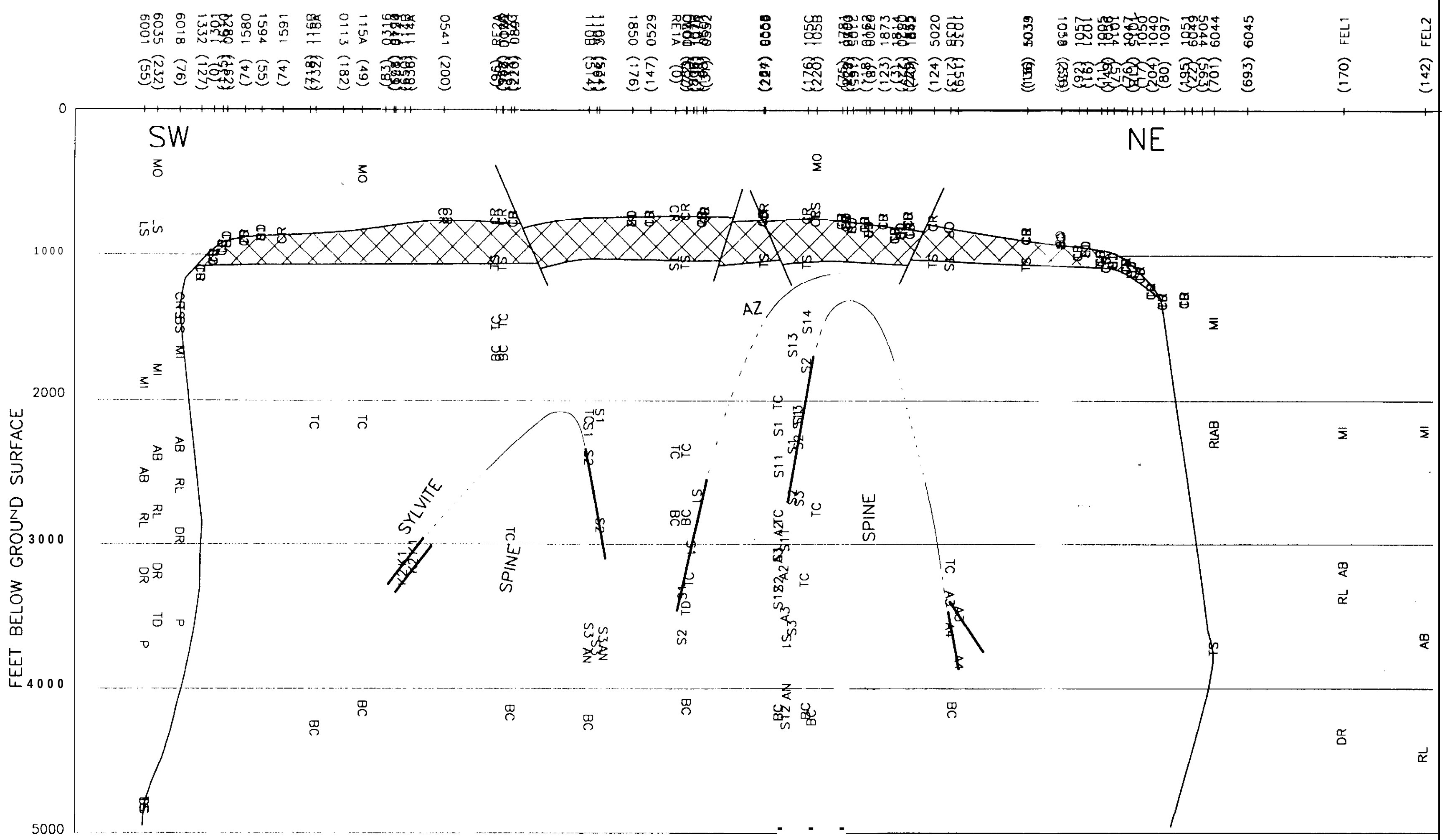

LEGEND

AN ANHYDRITE
S SHALE
K SYLVITE
CAPROCK

NOTES

1. SEE TABLE 1 FOR UNIT IDENTIFICATION
2. SEE FIGURE 1 SECTION 3

0 1000 2000
SCALE
FEET

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BRYAN MOUND SALT DOME

SALT STOCK INTERNAL STRUCTURE THROUGH CAVERNS 106– 110

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FIGURE 3A

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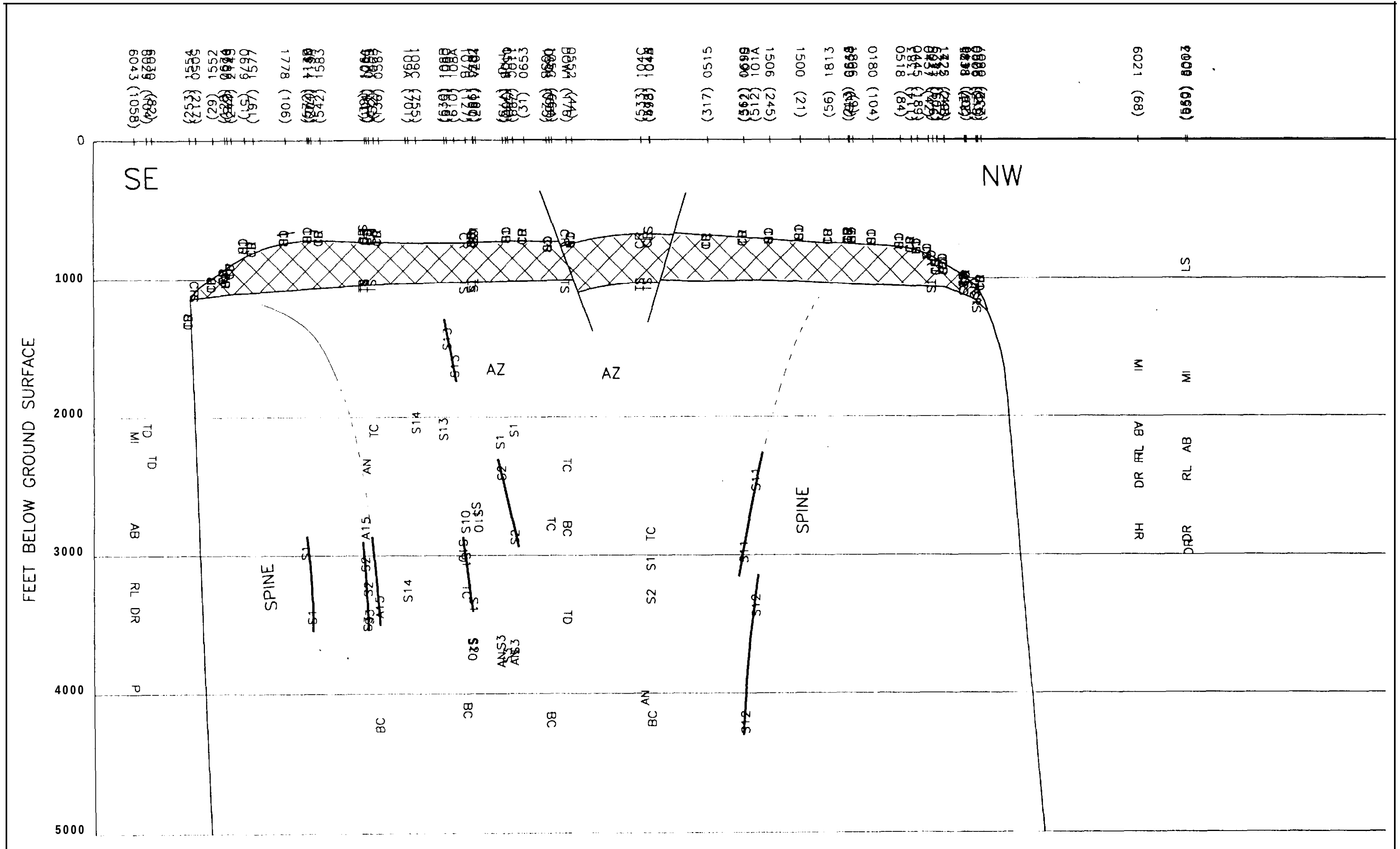

LEGEND

AN ANHYDRITE
S SHALE
K SYLVITE
CAPROCK

NOTES

1. SEE TABLE 1 FOR UNIT IDENTIFICATION
2. SEE FIGURE 1 SECTION 4

0 1000 2000
SCALE
FEET

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BRYAN MOUND SALT DOME

SALT STOCK INTERNAL STRUCTURE
THROUGH C A V E , :, 1 0 6 - 1 1 0

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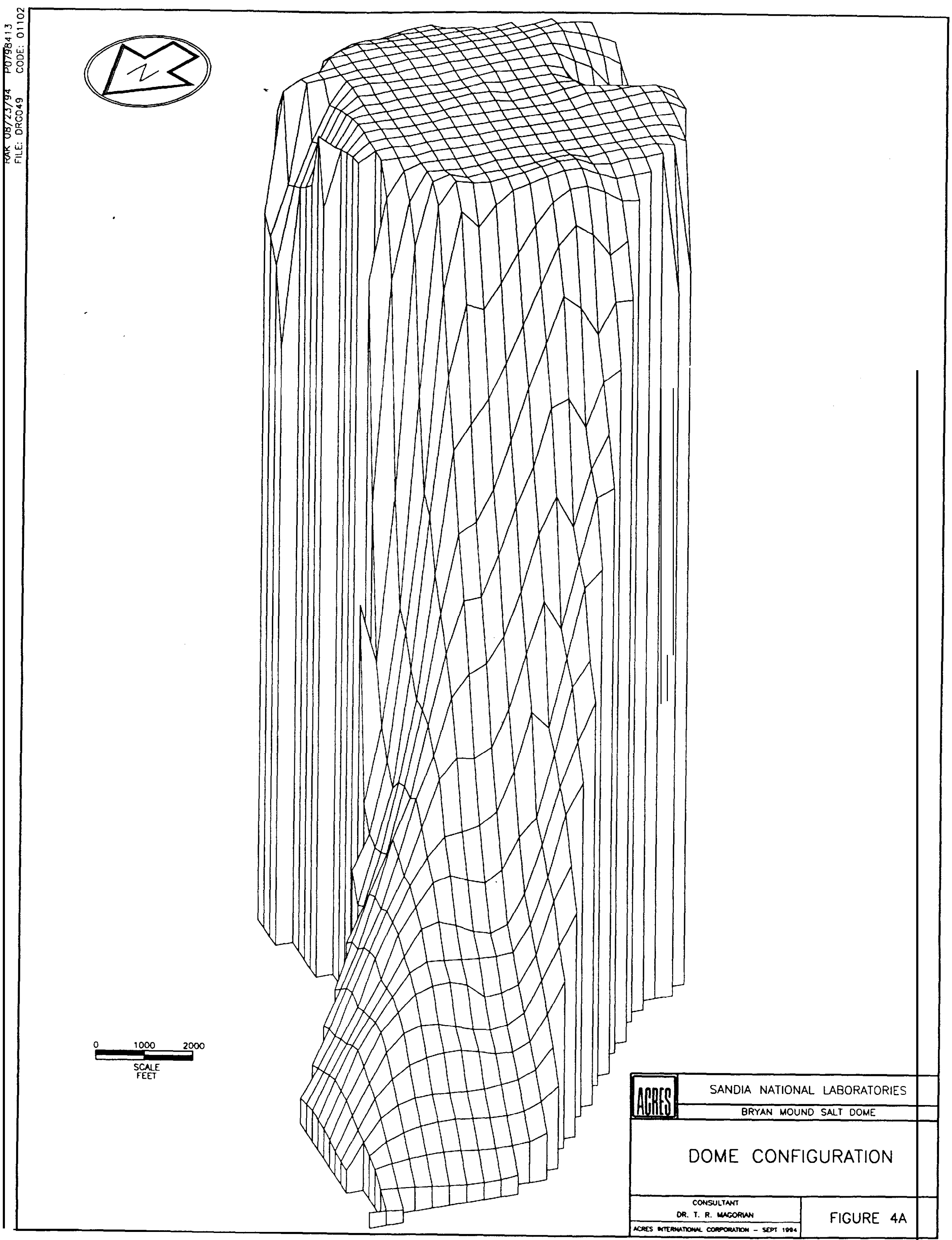
FIGURE 3B



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BRYAN MOUND SALT DOME

DOME CONFIGURATION

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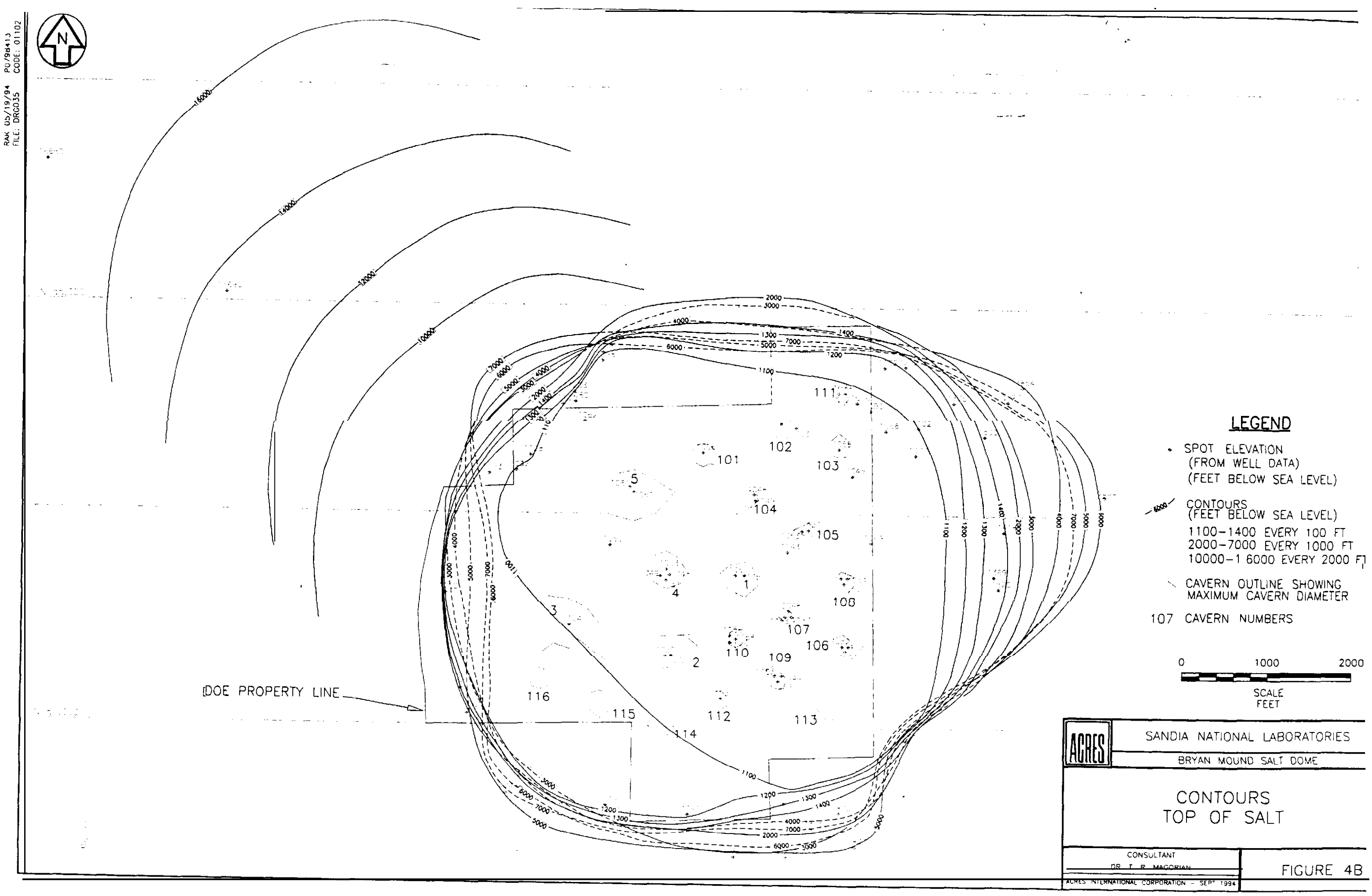
FIGURE 4A



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N
LEGEND
SPOT ELEVATION (FROM WELL DATA) (FEET BELOW SEA LEVEL)
CONTOURS (FEET BELOW SEA LEVEL)
1100–1400 EVERY 100 FT
2000–7000 EVERY 1000 FT
10000–16000 EVERY 2000 FT
CAVERN OUTLINE SHOWING MAXIMUM CAVERN DIAMETER
107 CAVERN NUMBERS
0 1000 2000
SCALE FEET
DOE PROPERTY LINE
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BRYAN MOUND SALT DOME
CONTOURS
TOP OF SALT
CONSULTANT
FIGURE 4B

In the previous characterization report, the deep well data to the northwest was assumed to be part of an enormous conical salt mass. Such huge salt bodies, while generally accepted at the time, were never supported by gravity or other geophysical information and have now been shown to be impossible because the weak 40 milligal gravity anomaly makes a salt cone unlikely, thus also indicating the southeast-leaning salt stock. In fact, we know that salt domes grow not just from salt ridges, but from relatively shallow salt sills, with thick sediments beneath them.

Several shallow overhangs were mapped in the 1980 characterization, as interpreted from the 20 radial refraction profiles. The data at the edge of the salt stock is good only to 250 feet, and down to little more than half the depth of the central well. Since the central well was only 6 173 feet deep, overhangs down to -3000 feet may be imaged. The largest of these is the northwest overhang parallel to the outer flat on the caprock, which may cut out almost 1000 feet of salt on the northwest corner of the dome; however, this estimate has considerable uncertainty. While it may be the result of the arcuate fault on the south side (described below), it is difficult to fit the sediment dips and convergences found on the NW-SE cross-section **(Figure 11)**. To most accurately resolve this uncertainty (if additional storage space were needed on this flank, for example), a modern Vertical Seismic Profile (VSP) or "Salt Proximity " survey would be required, hanging hydrophones in Cavern 5.

On the south side, an arcuate listric normal fault, concave against the dome, traps the oil found in the single productive well. Detailed drilling in and around this well shows clearly that the overhang formed by the fault does not extend more than a few hundred feet under the minor salt bulge. The south side overhang has been extended westward and back over 500 feet under the salt based on the same evidence, eliminating a possible cavern location. This could be resolved by another VSP, using hydrophones located in Cavern 115. The mechanism of this arc failure of steep sediments is indicated on the N-S cross section **(Figure 9),** where the fault is shown.

It appears that these overhangs may have been exaggerated in some earlier interpretations in order to develop oil prospects. However, it is also evident their lack of accurate mapping presents significant limitations in developing the full storage potential of this logistically well- situated dome, i. e., its location relative to transshipment connections.

2.3.3 Salt Stock External Structure

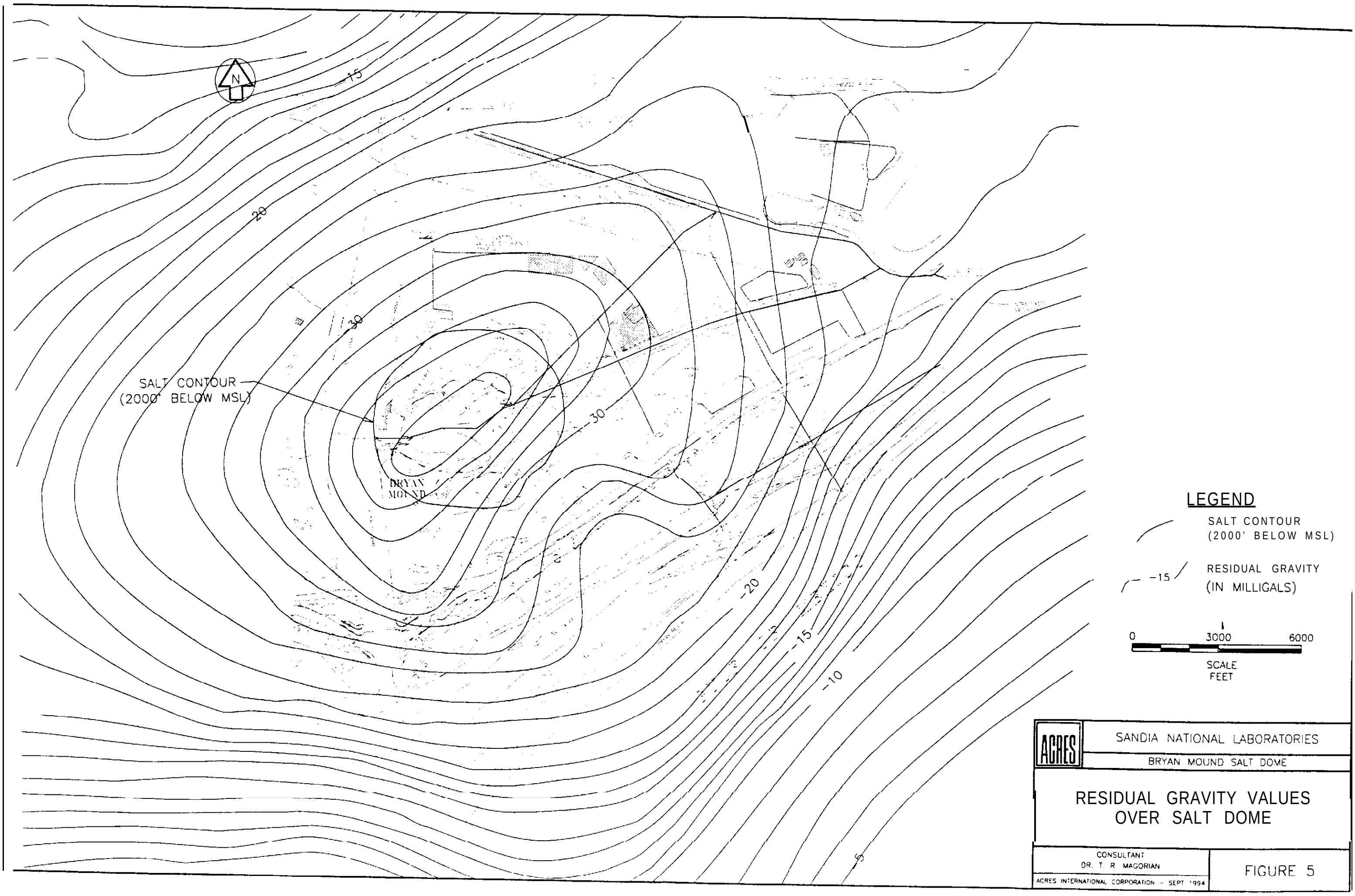
In almost all circular domes, *radial faults* are created as the rising salt mass punctures through the overlying sediments and drags surrounding sediments upwards until they tear apart. Thus, close to the salt edge or wall, the steep sediments are tangentially or radially faulted. Some of the most important of such faults are the arcuate or curved tangentials discussed above; however, additional radial faults are known at the southeast corner of the salt stock and may be present elsewhere. The limited well control around the dome results from the very minimal hydrocarbon production and exploration, which makes it diffrcult to locate all such radial faults, and thus the detailed geometry of the salt edge.

The salt stock leans slightly to the southeast. This has been proven down to 16,630 ft in the two deep wells on the northwest flank that penetrate salt under the thick geopressured shale. The bulge on the east side at 5000 feet might suggest that the dome is a huge cone of salt. However, the gravity anomaly northwest of the oil storage, only some 40 milligals at Bryan Mound, makes the salt cone highly improbable and thus indicating that the entire salt stock is leaning to the southeast **(Figure 5).**

Reflection seismic data that is obtained for oil and gas exploration, in which the salt stock flank is not imaged, is often adequate to define the flanks of a piercement dome, provided the sediment reflections are properly migrated, and the caprock does not overhang the salt edge. Unfortunately, at Bryan Mound, the highly-sulfurous caprock overhangs in exactly this way, down to the top of the Miocene.

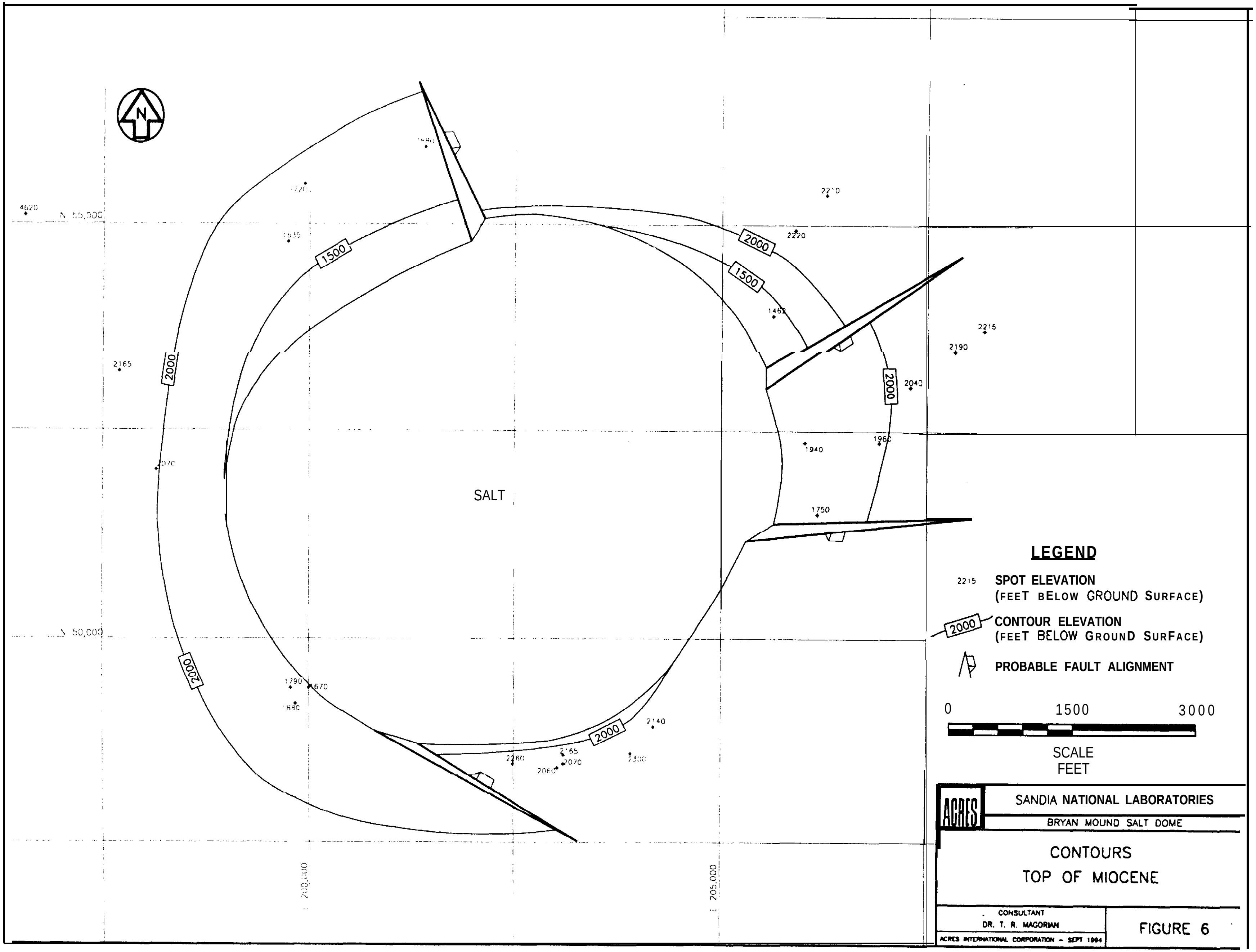
At the top of the Miocene **(Figure 6),** the well control shows an essentially circular salt stock, with a down-to-the-coast radial fault on the northwest corner, a horst block (a pair of radial faults converging upward) on the northeast comer, and an apparent tangential growth fault on the south side trapping oil against the salt in the single productive well.

A *large regionaZfGluZt* on the northwest side creates a flat spot on the salt stock which is otherwise almost perfectly circular. Its continuation around the north side is almost unknown because only two shallow wells penetrate sediments within the area of domal convergence. This may be part of a large arcuate listric normal fault, down-to-the-coast, which is tied to the side of the dome and extends to the northeast. The faulted feature drilled by the Feldman and



N
15
20
30
30
SALT CONTOUR
(2000' BELOW MSL)
BRYAN MOUND
20
15
10
5
LEGEND
SALT CONTOUR
(2000' BELOW MSL)
-15
RESIDUAL GRAVITY
(IN MILLIGALS)
0
3000
6000
SCALE
FEET
ACRES
SANDIA NATIONAL LABORATORIES
BRYAN MOUND SALT DOME
RESIDUAL GRAVITY VALUES
OVER SALT DOME
CONSULTANT
DR. T. R. MAGORIAN
ACRES INTERNATIONAL CORPORATION - SEPT 1994
FIGURE 5

RAK 08/24/94 PO798413
FILE DRG028 CODE. 01102



other wells, and beyond appears to be a radial horst block bounded by a radial fault extending northeast from the salt stock. A tangential fault apparently bounds the overhang on the south side, creating the trap for the limited oil production.

2.3.4 Shale Sheath and Convergence of Sediments on Dome Flanks

The Anahuac shale forms a mobile sheath around most of the salt stock below **3000 A (Figure 7).** At geopressure, this light volcanic-ash-rich mud has floated up with the salt to form an impenetrable hydrological barrier if a cavern were to be leached inadvertently to the edge of the salt. This is especially noticeable on the east side of the dome. The possibility of large inclusions in the salt along the deep flanks is remote, although highest near the major fault zones, since these and the anomalous zones are associated with important inclusions found in, mines. Although the flat top of the dome is irregular in detail with karst solution features, the steep flanks are remarkably free of detailed irregularities, commensurate with the faulted nature of their intrusive origin.

Convergence of sediments on the flanks can be used both to locate the edge of the salt stock in the absence of penetrating wells, and to calculate the rate of stock growth. Little convergence is apparent in the geopressured Anahuac but increases through the deltaic Miocene sand pile, reaching its maximum on the northwest side under the Pliocene unconformity. Limited convergence is found in areas of overhang. None of the overhangs above 10,000 feet show any evidence of being more than a few hundred feet deep horizontally into the salt, including the oil-bearing south side which has been drilled with several side-tracked holes.

2.4 Structural Interpretation

The interpretations described in the preceding paragraphs are significant in understanding safety margins for existing cavems and for establishing possible locations for additional caverns. The structural interpretations can best be understood by viewing the cross-sections presented in Figures g-12.

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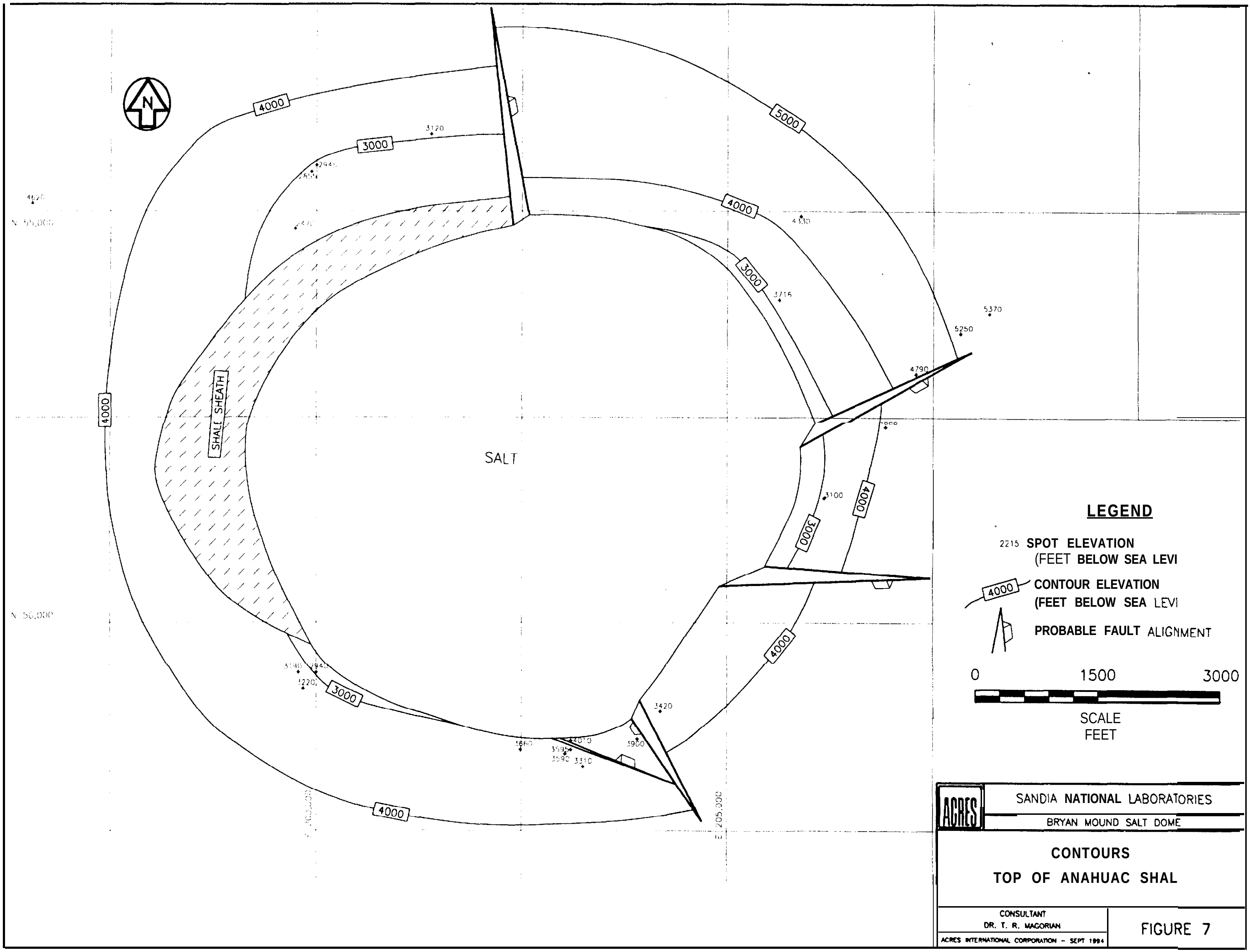


2.4.1 Geologic Cross-Sections

The major changes that affect the subsurface geologic profiles shown in the previous 1980 characterization involve the overall dip of the deep salt stock and the location and depth of the shale sheath and shallow overhangs. Most of these differences involve the extrapolated interpretation of the 1949 refraction seismic survey since there is little change in the amount or interpretation of subsurface data.

East-West: **(Figure 8)**

The bulge on the east side of the dome is no longer believed to persist with depth. A significant change is discovery of a wide shale sheath below the middle Miocene (Alpine) UNCONFORMITY. The shape of the salt edge inside this geopressured sheath is unknown on this flank and may limit expansion of cavern storage until additional data is obtained. The summary of these flanks (Table 5 and Figure 16) indicate what is needed for possible expansion.

North-South: **(Figure 9)**

The overhang on the south side is essentially the same as mapped previously, although not included in any of the sections in the previous characterization. The north flank is still unknown.

Southwest-Northeast: **(Figure 10)**

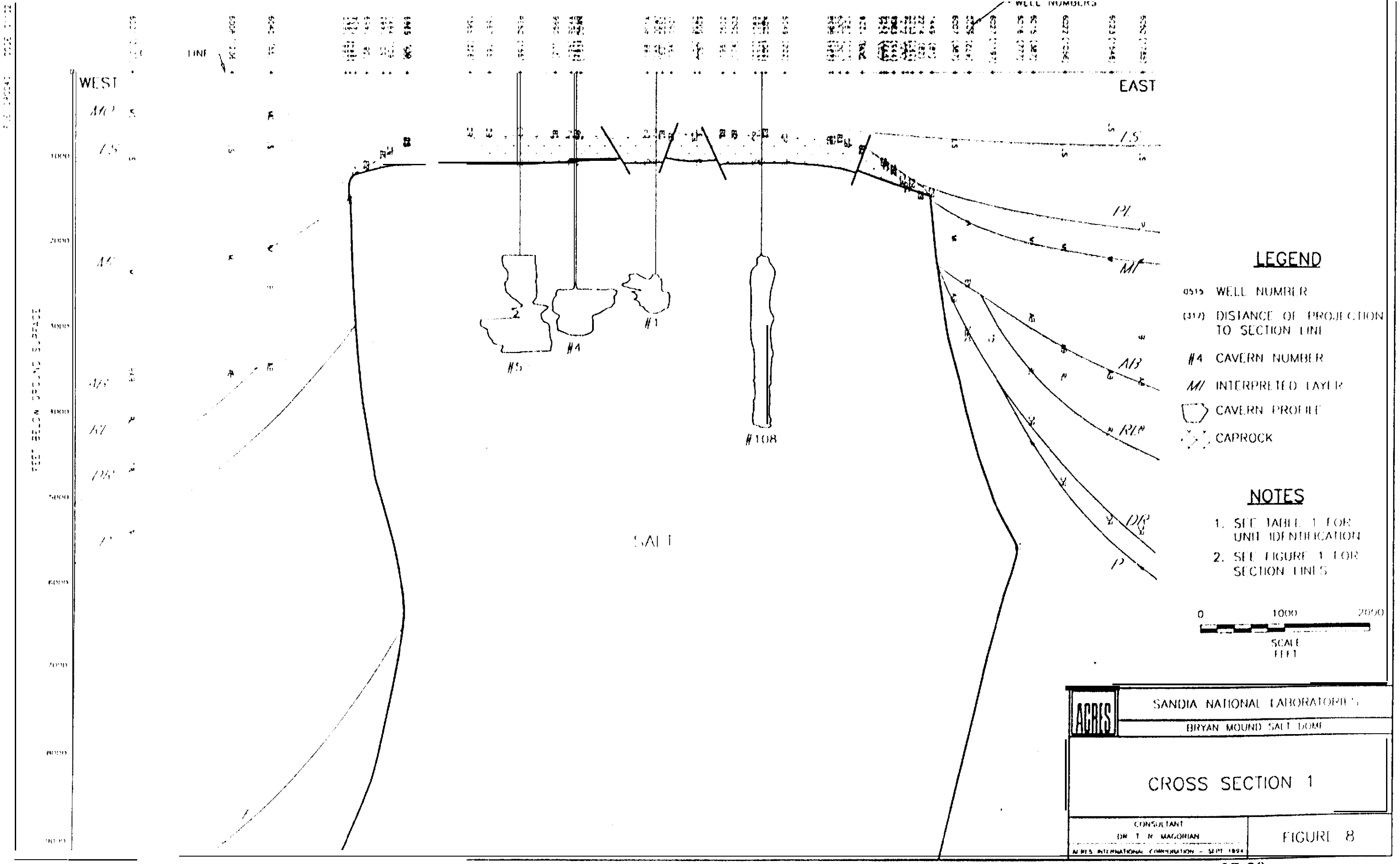
This section shows little change from the previous characterization. The deep orientation of the salt stock is still unknown, although an overhang should develop below 5000 feet.

Northwest-Southeast: **(Figure 11)**

The most important cross-section through the dome runs from the deep Exxon (Humble) and Tenneco (Houston Oil and Minerals) wells up the northwest flank of the salt stock. The lower Miocene sands are present in the Freeport A3 but are absent nearer the salt stock in the Texaco 8, along with oil shows, indicating a wide shale sheath, possibly bounded by a large fault. The southeast flank is unknown and only assumed to be parallel. Sediment convergence indicated no significant overhang above 5000 feet.

2.4.2 Anomalous Zones

The *anomalous zones* **(AD)** show as linear depressions, actually grabens, on the caprock upper surface. They are bounded by normal faults which meet at the top of salt. The principal northwest-southeast AZ is apparent on the caprock contours and is congruent with the gravity flexure and external structural features at depth **(Figures 5 and**



WEST
EAST
FEET BELOW GROUND SURFACE
LINE
WELL NUMBERS
SALT
#5
#4
#1
#108
LEGEND
0515 WELL NUMBER
(317) DISTANCE OF PROJECTION TO SECTION LINE
#4 CAVERN NUMBER
MI INTERPRETED LAYER
CAVERN PROFILE
CAPROCK
NOTES
1. SEE TABLE 1 FOR UNIT IDENTIFICATION
2. SEE FIGURE 1 FOR SECTION LINES
0 1000 2000
SCALE FEET
ACRES
SANDIA NATIONAL LABORATORIES
BRYAN MOUND SALT DOME
CROSS SECTION 1
CONSULTANT DR. T. R. MAGORIAN
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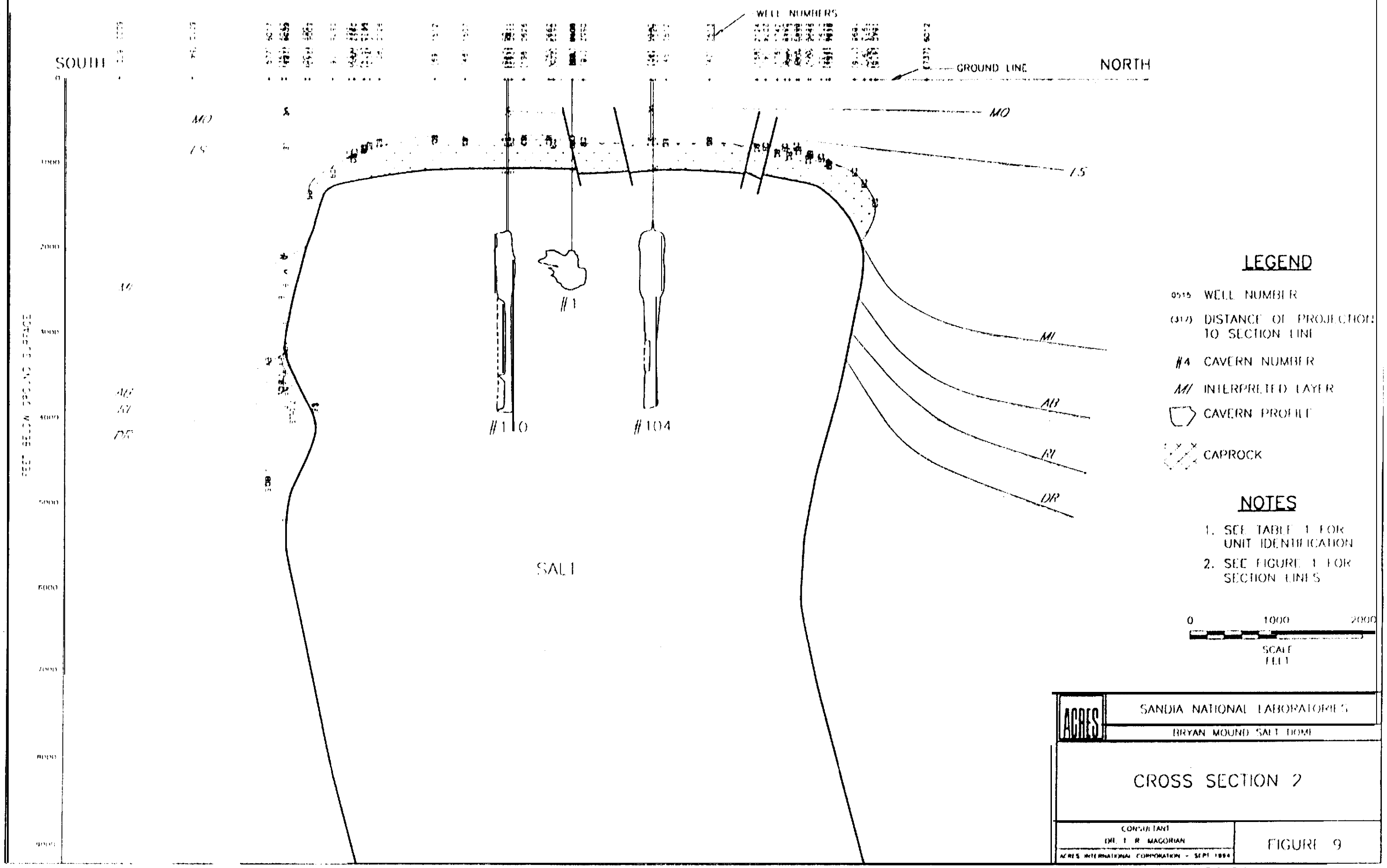
FIGURE 8

27-28



SOUTH
NORTH
WELL NUMBERS
GROUND LINE
FEET BELOW GROUND SURFACE
MO
TS
MI
AB
RI
DR
SALT
#110
#1
#104
LEGEND
WELL NUMBER
DISTANCE OF PROJECTION TO SECTION LINE
#4 CAVERN NUMBER
MI INTERPRETED LAYER
CAVERN PROFILE
CAPROCK
NOTES
1. SEE TABLE 1 FOR UNIT IDENTIFICATION
2. SEE FIGURE 1 FOR SECTION LINES
0
1000
2000
SCALE
FEET
ACRES
SANDIA NATIONAL LABORATORIES
BRYAN MOUND SALT DOME
CROSS SECTION 2
CONSULTANT
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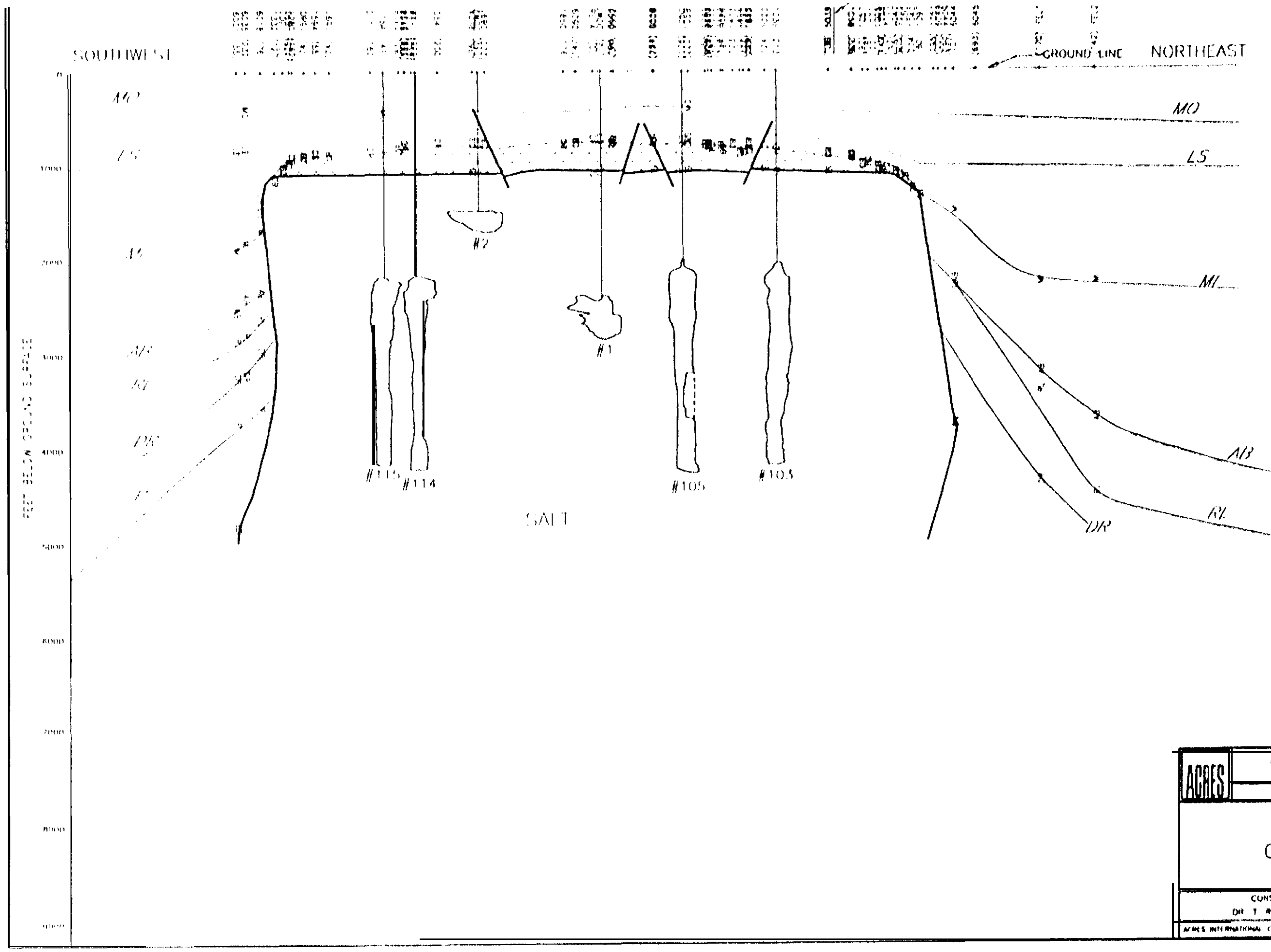
FIGURE 9



LEGEND

- 0515 WELL NUMBER
- (117) DISTANCE OF PROJECTION TO SECTION LINE
- #4 CAVERN NUMBER
- MI INTERPRETED LAYER
- CAVERN PROFILE
- CAPROCK

NOTES

1. SEE TABLE 1 FOR UNIT IDENTIFICATION
2. SEE FIGURE 1 FOR SECTION LINES

0 1000 2000
SCALE FEET

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BRYAN MOUND SALT DOME

CROSS SECTION 3

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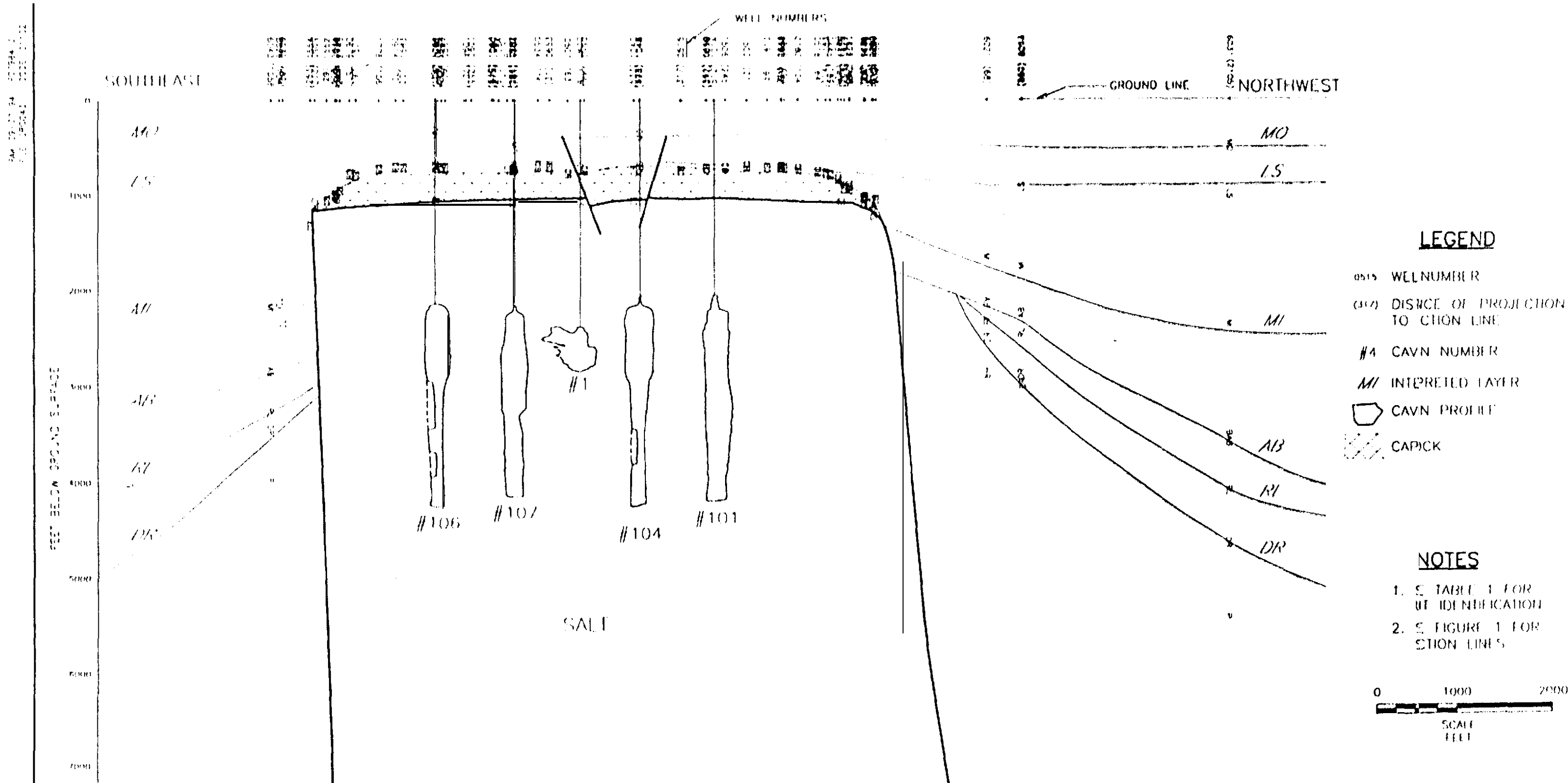
FIGURE 10



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SANDIA NATIOL LABORATORIES

BRYAN MOD SALT DOME

CROSS SECION 4

CONSULTANT

DR. T. R. MAGORIAN

ACRES INTERNATIONAL CORPORATION

FIGNE

7). At least one more AZ almost normal to it appears to be present, segmenting the salt stock into at least four discrete lobes. The north-northeast / south-southwest trending AZ is evidenced by more subtle surface topographic expression, by external structure manifested at depth, and by internal structural features in the salt, as observed on well logs. In salt stocks this large, four or more spines (lobes) are usually present; thus Bryan Mound appears typical, The limited expression of the A.& indicates strong water flow through the caprock, typical of the Brazos deltaic sands the dome is buried in.

2.4.3 Correlation of Geologic Features with Gassy Caverns

The occurrence of excessive dissolved gas in the oil at several SPR caverns has led to much speculation regarding both the origin and future trends. The association of the gas with known geologic features in the dome is speculative at this time, but some evidence suggests that the AZs may be conduits for higher gas permeability. More complete discussion of this association is contained in Section 2.4.2. and 3.1.2.

3 SPR SYSTEM CONSIDERATIONS

3.1 Cavern Configurations

Table 2 was compiled by DynMcDermott Petroleum Operations and lists the most relevant parameters associated with cavern integrity. All depths are given in feet below the bradenhead flange (which varies from about 4.4 to 16.5 A amsl), but cavern-induced subsidence is very gradually lowering the surface. A brief description of the data follows:

"Cavern number" is shown on **Figures 1** (base map), 13, and the **Frontispiece.**

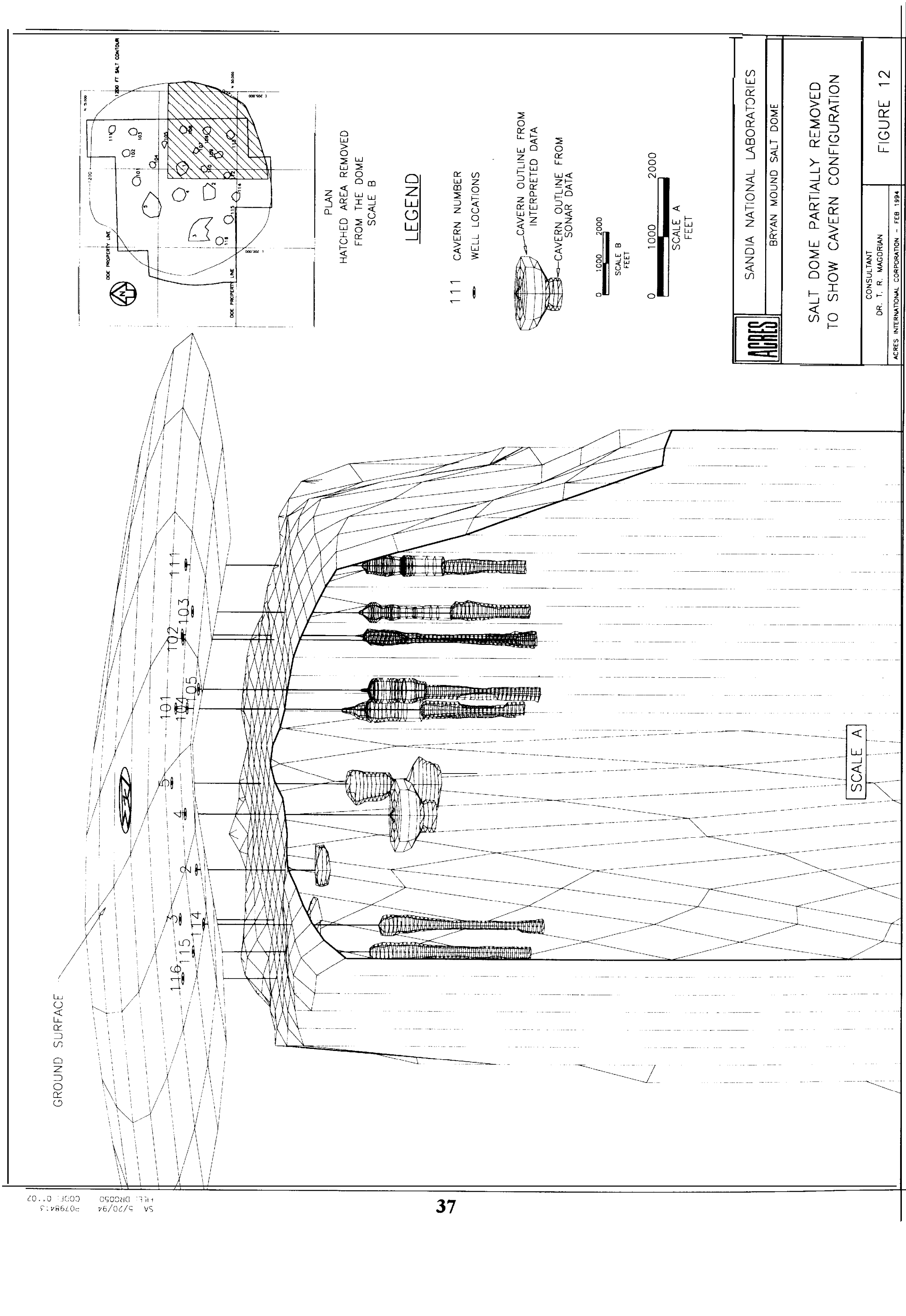
"Year started" indicates initial startup of leaching, but does not include workovers, etc., performed subsequently for SPR modification.

"Cavern volume," in millions of barrels, is usually about 10% larger than the volume of stored material, allowing for brine in the cavern bottom.

Table 2 Bryan Mound Cavern Geotechnical Parameters

CAVERN	SPR BM 1	SPR BM 2	SPR BM 4	SPR BM 5	SPR BM 101	SPR BM 102	SPR BM 103	SPR BM 104	SPR BM 105	SPR BM 106	SPR BM 107	SPR BM 108	SPR BM 109	SPR BM 110	SPR BM 111	SPR BM 112	SPR BM 113	SPR BM 114	SPR BM 115	SPR BM 116
YEAR STARTED	1942	1942	1942	1957	1982	1980	1982	1980	1980	1980	1980	1980	1980	1980	1983	1980	1984	1984	1984	1984
NUMBER																		2	2	2
CAVERN VOLUME, MMB	8246	6232	20368	37387	11223	11252	11243	11B.7	11239	12345	1134	12317	11357	11342	11221	10298	7207	8.23	10.32	10.74
TOP CAPROCK	-730	-766	-760	-720	-734	-824	-852	-755	-776	-729	-756	-760	-725	-765	-938	-747	-845	-860	-865	-890
TOP SALT	-1136	-1070	-1065	-1090	-1062	-1067	-1063	-1058	-1064	-1065	-1073	-1073	-1085	-1075	-1078	-1064	-1066	-1074	-1079	-1086
CASING SEAT	-2166	-1376	-1496	-1928	-1995	-1994	-1990	-1987	-1971	-1980	-1992	-1980	-1970	-1988	-1961	-1979	-2004	-2005	-2011	-2006
TOP CAVERN	-2349	-1450	-2495	-2102	-1998	-2203	-2122	-2108	-2050	-2106	-2150	-2166	-2132	-2140	-2130	-2065	-2134	-2130	-2146	-2100
BOTTOM CAVERN (DATE)	-2762 (9/92)	-1670 (3/93)	-3076 (10192)	-3273 (1193)	-4159 (10/92)	-4237 (3/93)	-4133 (4/91)	-4163 (2/93)	-4193 (12/92)	-4011 (12/92)	-4097 (11192)	-4130 (6/93)	-4176 (2/93)	-4122 (3/93)	-4128 (12/92)	-4105 (2/93)	-4200 (1193)	-4166 (1/93)	-4130 (1193)	-3945 (10192)
CAVERN HEIGHT(H)	413	220	581	1171	2161	2034	2021	2055	2143	1905	1947	1964	2044	1982	1998	2040	2066	2036	1984	1845
DIAMETER (D)	383	453	504	481	193	201	201	202	195	216	205	211	201	203	200	196	156	170	193	204
H/D	1.08	0.49	1.15	2.43	11.20	10.12	10.05	10.17	10.99	8.82	9.50	9.31	10.17	9.76	9.99	10.41	13.24	11.98	10.28	9.044
NEAREST CAVERN	4	3	1	4	104	103	111	101	108	107	1	105	110	1	103	110	109	115	114	115
PILLAR THICKNESS(P)	237	450	237	320	469	577	414	469	425	476	329	425	426	417	414	451	438	492	492	517
P/D	0.62	0.99	0.47	0.67	2.43	2.87	2.06	2.32	2.18	2.20	1.60	2.01	2.12	2.05	2.07	2.30	2.81	2.89	2.55	2.53
ROOF THICKNESS(B)	1213	380	1430	1012	936	1136	1049	1050	986	1041	1077	1093	1047	1065	1052	1001	1068	1056	1067	1014
B/D	3.17	0.84	2.84	2.10	4.85	5.65	5.22	5.20	5.06	4.82	5.25	5.18	5.21	5.25	5.26	5.11	6.85	6.21	5.53	4.97
DISTANCE TO EDGE (E)	2410	1870	2290	1470	1490	1110	1220	1990	2310	1050	1800	1670	1430	2080	590	1340	680	1100	980	580
E/D	6.29	4.13	4.54	3.06	7.72	5.52	6.07	9.85	11.8	4.86	8.78	7.91	7.11	10.25	2.95	6.84	4.36	6.47	5.08	2.84
DISTANCETO PROPERTYLINE	1360	715	1580	680	490	210	180	970	580	230	820	220	820	1310	240	860	340	219	115	273
BHF ELEVATION JAN 1993	13.1	16.6	128	7.6	4.4	5.1	6.6	10	13.8	159	16.1	15.7	16	159	16	165	0	0	8	9

Data current to July, 1993, with 1994 estimates of distance to edge (E)



SANDIA NATIONAL LABORATORIES
BRYAN MOUND SALT DOME
SALT DOME PARTIALLY REMOVED
TO SHOW CAVERN CONFIGURATION
FIGURE 12
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ACRES
PLAN
HATCHED AREA REMOVED
FROM THE DOME
SCALE B
LEGEND
111 CAVERN NUMBER
WELL LOCATIONS
CAVERN OUTLINE FROM
INTERPRETED DATA
CAVERN OUTLINE FROM
SONAR DATA
0 1000 2000
SCALE B
FEET
0 1000 2000
SCALE A
FEET
GROUND SURFACE
SCALE A
116 115 114 3 2 4 5 104 101 105 102 103 111

"Top of caprock and salt," respectively, are the uppermost surfaces of those units, with values averaged between the multiple wells.

"Casing seat," and **"cavern top"** (or bottom) is self-explanatory.

"Cavern **Height (H)"** is the distance from cavern top to bottom.

"Diameter (D)" is the constructed diameter, which is an idealized (average) cylinder diameter that would correspond to the final cavern volume with the given height.

ttH/Dt' is the ratio of the cavern height to the constructed diameter, providing a measure of the cavern shape.

"Pillar thickness (P)" is the thickness of the pillar of salt between a cavern and its nearest neighbor.

"P/D" is the ratio of the pillar thickness and the constructed diameter, providing a relative measure of mechanical integrity.

"Roof thickness (B)" is the distance between the top of the cavern and the top of salt.

"B/D" is the ratio of the roof thickness to the constructed diameter, providing a measure of mechanical integrity.

"Distance to dome edge (E)" is the estimated distance between the cavern and the outside edge of dome salt.

"ED is the ratio of the distance to the edge of dome to the constructed diameter, providing a measure of mechanical integrity.

"Distance to property line" is the closest distance between the cavern edge and the SPR property line.

"BHF Elevation" is the bradenhead flange elevation in 1988, rounded to 0.1 ft.

The values shown in **Table 2** reflect the very conservative design approach used throughout the SPR system, especially for Caverns BM 101-l 16. The preexisting cavems (BM 1, 2, 3, 4, 5) do not follow those same guidelines, of course, but there have been few instability or safety issues associated with them. Cavern 3 was judged to be marginally unsuitable for oil storage, owing to its "pancake" shape, its generally shallow depth near the top of salt, and pressure integrity questions; thus it was plugged and abandoned. The shallow depth of Cavern 3 from 1520-1715 A leaves open the possibility for an additional cavern beneath, but offset laterally (see Section 3 5, "Expansion Cavem Possibilities").

3.1.1 SPR Cavern Shapes

The following drawings **(Figs. 12-14)** represent our best estimate of cavern configurations within the Bryan Mound salt stock based on available information, including cavern leach and fill data, and sonar records. However, sonar plots were incomplete, because of the inability to obtain sonar in oil during leach and fill operations. Thus, some caverns are shown with dashed boundaries to show where known storage volume exists, but wall geometry is uncertain.

Figure 12 shows an isometric view of the southeast quadrant of the salt stock.

Figure 13 shows the two-dimensional configuration of the storage caverns.

Figure 14 shows isometric representations of the storage caverns.

3.1.2 Cavern Integrity Issues

<u>Cavern 1</u>

Cavern 1 is located well away from the edge of the dome but its closest approach to Cavern 4 is only 237 ft, less than now required of new caverns. Although geomechanical modeling analyses by Preece and Foley [19841 show that Cavern 1 is structurally sound, there is a likelihood of coalescence with Cavern 4 after two or three drawdowns. Such an eventuality would create an extremely large cavern and if joined with Cavern 5 would approach 100 MMB **(Figures 12,14).** However, the sonar and separation analysis of caverns following drawdowns should preclude such an eventuality from happening.

<u>Cavern 4</u>

Cavern 4 is the second largest cavern in the SPR system, with a volume of nearly 20.7 million barrels, exceeded only by Cavem 5 with 3 7.9 million barrels. A failure of the cemented casing in Well 4 at a depth of 789 A caused oil to first start leaking into the caprock in September of 1982, and eventually some 44,000 barrels escaped (POSSI, 1983). The first indication of a leak was a gradual loss of oil pressure, but brine had been removed from the cavern at about that time and the loss was attributed to it, causing diagnostic difficulty. Although the potential for oil escaping the caprock into the accessible environment was judged very low at the time, the loss of oil was problematic and the cause of concern, because it could affect other caverns as well.

This was the third failure of casing within the prior sulfur mining zone, demonstrating the short life of casing exposed to hot acidic water. The cemented casing string in Well 3 failed in the late 1950's, and in Well 2 in the mid-l 970's. Drilling records from these wells were unavailable, so the degree of loss of cement while placing these cemented casing strings is unknown. Some of the difficulty no doubt is caused by incomplete cementing in loss zones, causing

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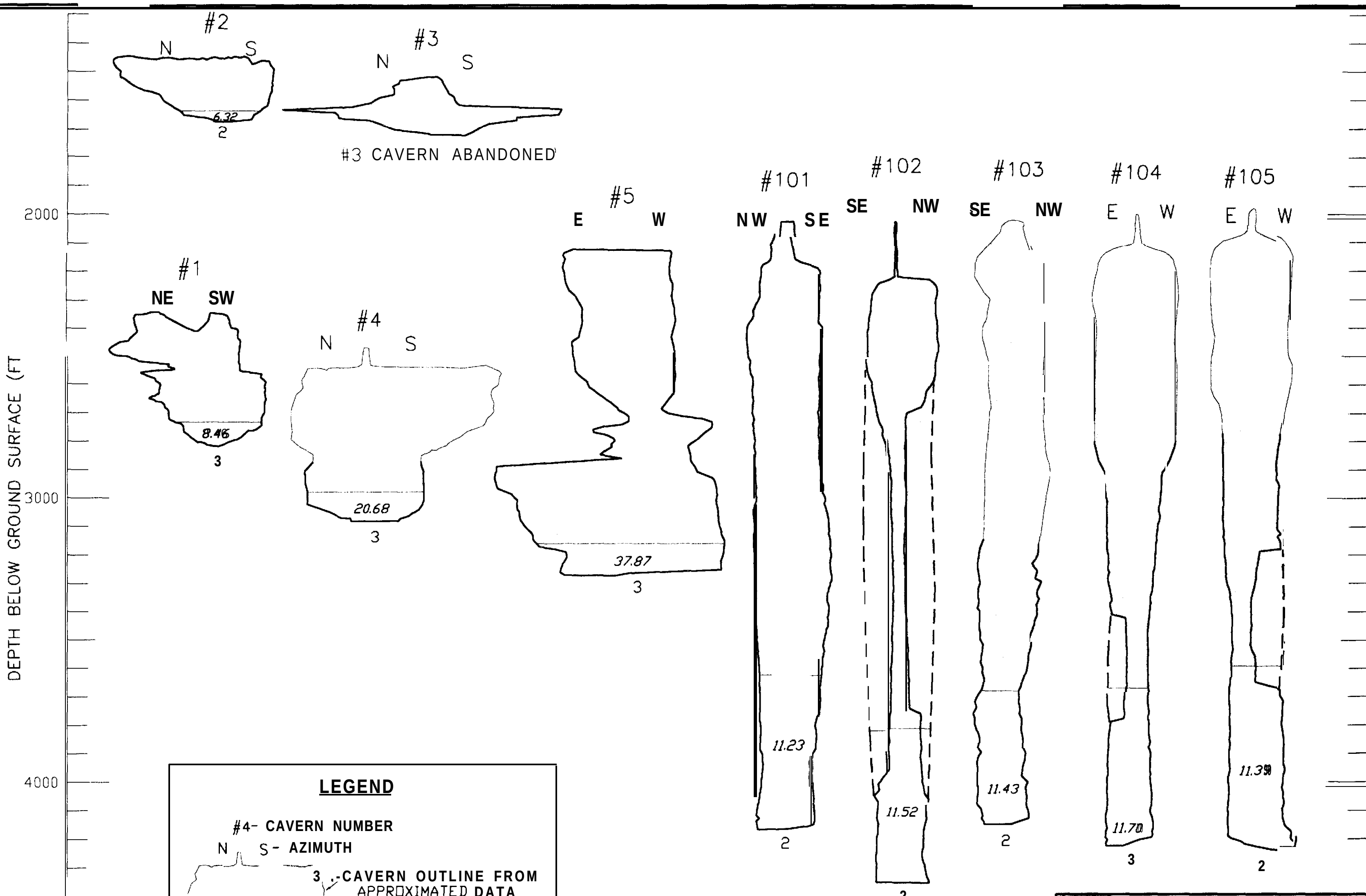
FILE: DRG037 CODE: 01102



LEGEND

#4- CAVERN NUMBER
N S - AZIMUTH
3 -CAVERN OUTLINE FROM APPROXIMATED DATA
CAVERN OUTLINE FROM SONAR DATA
20.68 BRINE/OIL INTERFACE
-CAVERN VOLUME IN MMB
3 NUMBER OF WELLS INTO CAVERN

NOTE:
DASHED LINES WHERE SONAR UNAVAILABLE

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STRATEGIC PETROLEUM RESERVE
CAVERN (COMPOSITE)

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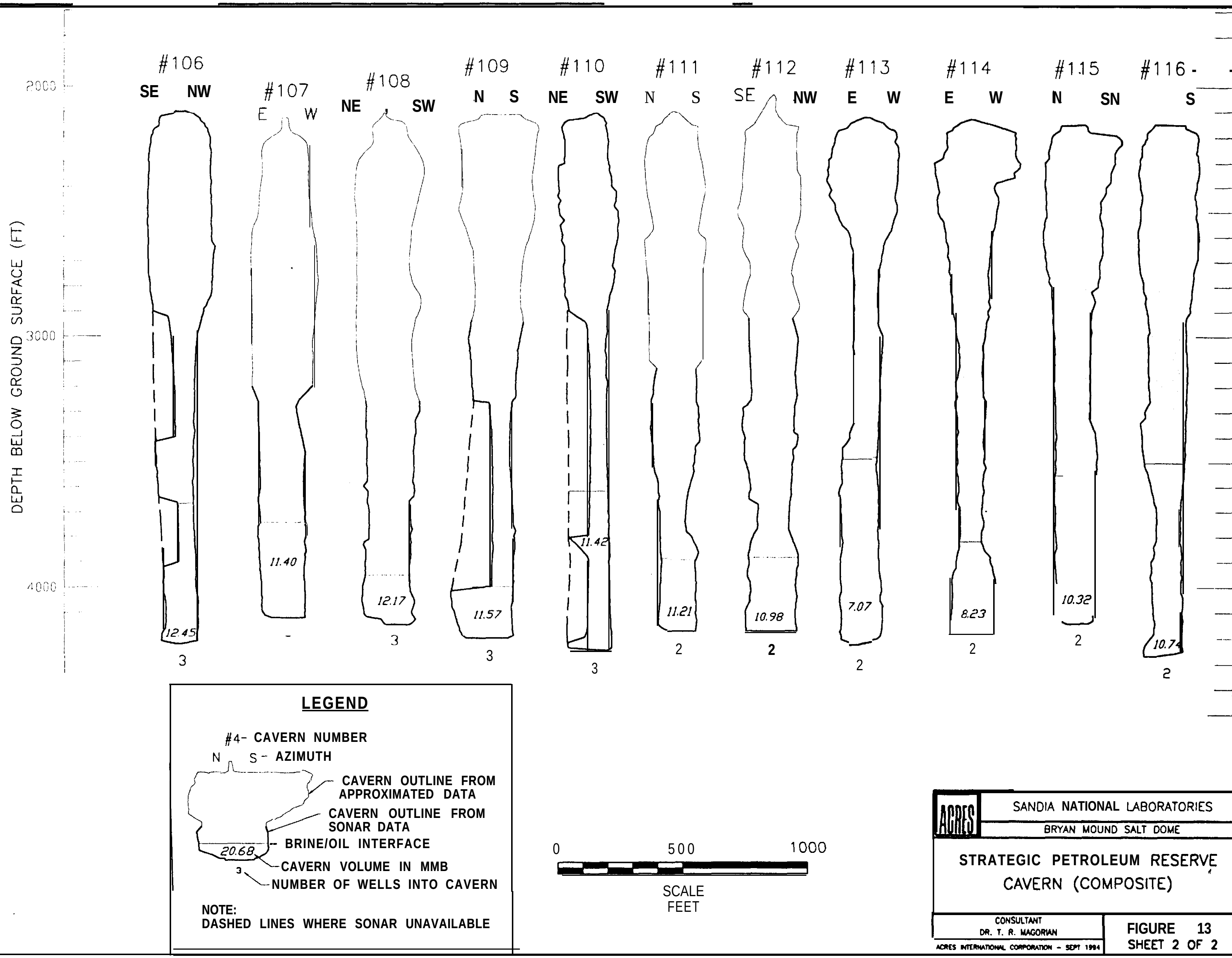
FIGURE 13
SHEET 1 OF 2

RAK 08/23/94 PO79841 3
FILE: DRG038 CODE 01102



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BRYAN MOUND SALT DOME

STRATEGIC PETROLEUM RESERVE
CAVERN (COMPOSITE)

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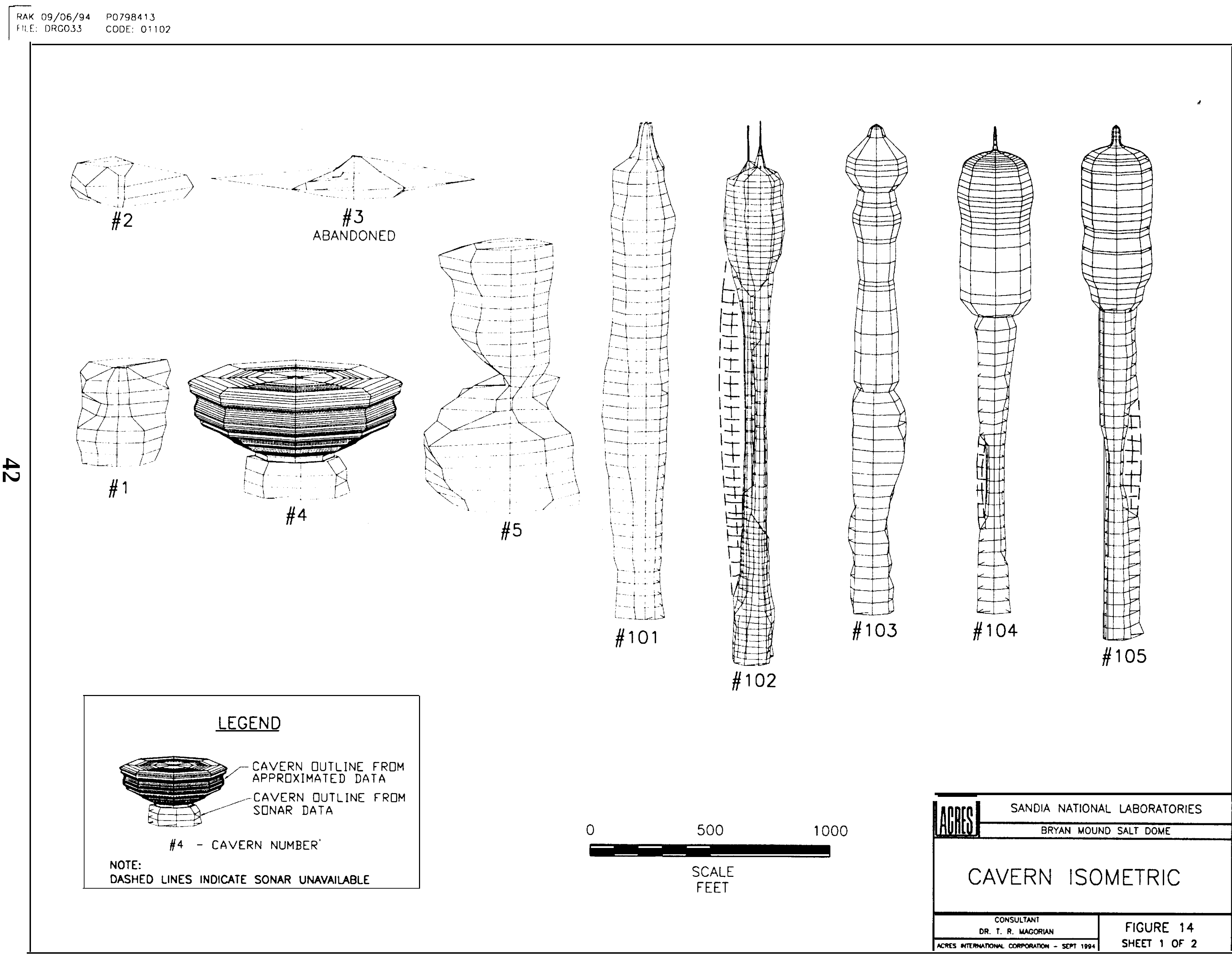
FIGURE 13
SHEET 2 OF 2



RAK 09/06/94 P0798413
FILE: DRG033 CODE: 01102
#2
#3
ABANDONED
#1
#4
#5
#101
#102
#103
#104
#105
LEGEND
CAVERN OUTLINE FROM APPROXIMATED DATA
CAVERN OUTLINE FROM SONAR DATA
#4 - CAVERN NUMBER
NOTE:
DASHED LINES INDICATE SONAR UNAVAILABLE
0
500
1000
SCALE
FEET
ACRES
SANDIA NATIONAL LABORATORIES
BRYAN MOUND SALT DOME
CAVERN ISOMETRIC
CONSULTANT
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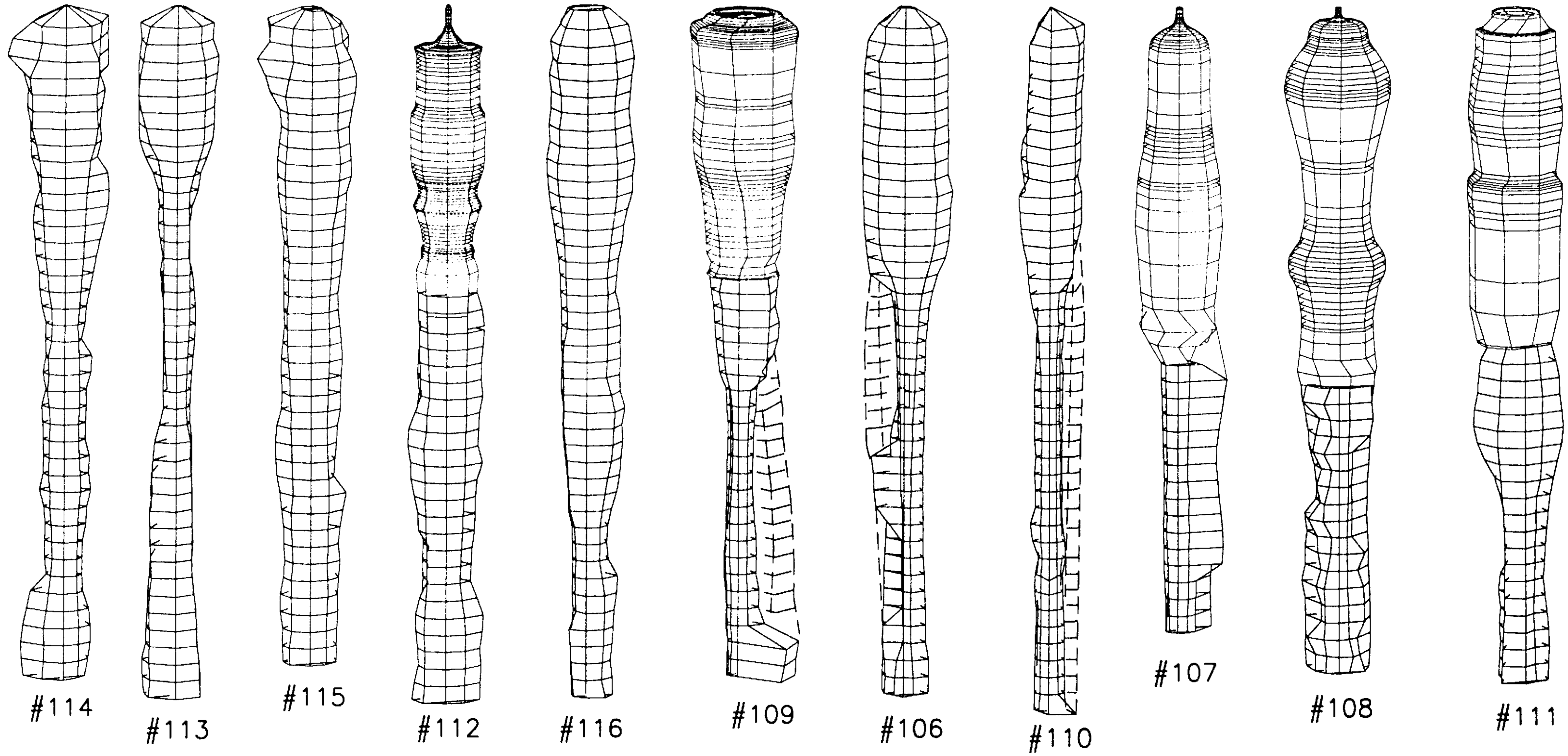
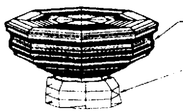
FIGURE 14
SHEET 1 OF 2

RAK 09/06/94 PO7984 13
FILE DRG034 CODE 01102



LEGEND



CAVERN OUTLINE FROM APPROXIMATED DATA
CAVERN OUTLINE FROM SONAR DATA

#4 - CAVERN NUMBER

NOTE:
DASHED LINES INDICATE SONAR UNAVAILABLE

0 500 1000

SCALE
FEET

ACRES

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BRYAN MOUND SALT DOME

CAVERN ISOMETRIC

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FIGURE 14
SHEET 2 OF 2

poor sealing. Well 4 was cemented and isolated from the cavern. Three Cavern 4 reentry wells, which had been constructed after SPR acquisition, remain. There has been no indication of other problems associated with this cavern (POSSI, 1983).

Although the wider-than-usual diameter of 504 ft and short height of 581 f't make for a stout shape, the geomechanical modeling of Preece and Foley [19841 suggest no structural problems, either present or future. The previously mentioned possibility for coalescence with Cavern 1 exists; this could create another super cavern, similar to Cavern 5.

Cavern 5

Cavern 5 is a two-lobed cavern with a total volume of nearly 38 million barrels, the largest by far in the SPR inventory. Because of this very large volume, combined with an irregular shape and protruding edges, this cavern has been the center of many questions involving structural integrity. In addition, there is a zone of high anhydrite content that inhibited leaching of the narrow neck that separates the two lobes. Also, the brine string in Well 5 has been damaged at least four times by apparent salt falls, and/or shifting of material from the upper lobe.

Preece and Foley [19841 noted that substantial separation from both the edge (the 650 fi distance has been increased to 1500 ft in this revision) and the caprock (1012 ft) enhanced the geomechanical environment for such a large cavern. Their analyses did not suggest any potential for instability, present or future, but they stated their model could not predict pillar stability during coalescence, or with underhanging wall projections.

An oil transfer was conducted in 1986 that leached the neck between the upper and lower cavern lobes, and also converted the cavern from sweet to sour oil storage. Leaching in April and May of 1986 created some 500,000 barrels of new space. This modification, along with additional leaching in June of 1987 which leached away the trap in the roof of the lower lobe, were aimed at improving structural integrity in the two-lobed cavern [BPS, 19901. However, since that time, there have been three incidents of presumed salt falls and associated damaged casing in Wells 5 and 5C.

The relative proximity of Cavern 5 to Caverns 4 and 1 was noted in the 1980 characterization. The enlargement of these caverns upon drawdown would create coalescence after 3-4 cycles; the interconnected gallery could have a combined volume approaching 100 million barrels **(Figures 12, 14).** The structural implications of such a large storage gallery have not been fully investigated, but are being considered at this time. As noted previously, the added proximity of Cavern 1 to Cavern 4 also must be considered. Mills (1994) notes that SPR Level II Criteria requires a study after every drawdown and that Cavern 5 would probably not be refilled if coalescence were possible during subsequent drawdown.

Salt Falls and Haneinp Striw Failures

Since 1978 and continuing to the present, there have been some 37 incidents in which portions of hanging strings have been damaged or lost **(Table** 3). Most of them occurred during a static operating mode, but some occurred during leach/fill, and a few happened during depressurization or workovers, so all are not necessarily similar events. The problem is somewhat unique to Bryan Mound, even though similar incidents have occurred elsewhere. There have been several reasons advanced as to why these hanging string failures have occurred, including association with anomalous zones, excessive gas emission from within the salt, and the presence of HZS, possibly associated with the predominantly sour oil stored in these caverns. Corrosion as a contributing factor has been largely ruled out, as I993 studies of metallurgy at the point of pipe joint failure in Cavern 107 showed no indications of corrosion due to hydrogen embrittlement. There appears to be no correlation of depth of failure with any other factor.

TO date, a satisfactory answer to this puzzling condition has not been agreed upon, including whether salt is actually physically falling. However, the evidence for a majority of the incidents seems to support salt falling in some manner, even though it has not been proved [Mills, 19941. Mills also cites other geotechnical distinctions about Bryan Mound which may have some bearing on the problem. There appears to be more heterogeneous salt, as shown in the more irregular Phase III caverns than those constructed at West Hackberry and Big Hill, for example. Some of the irregularities have been attributed to higher concentrations of sylvite, which typically leads to “wings” or unequal extensions in the caverns, often with preferred directional orientation. The stiffer, slower laboratory creep of Bryan Mound salt may also be a factor controlling large-scale mechanical behavior, according to Mills. He sees much slower transient response rates in Bryan Mound caverns following pressurization / &pressurization. However, the manner in which these geotechnical distinctions

Table 3 History of Bryan Mound Casing Failures[1]

Cavern Wells	Cavern Volume	Date Discovered	Activity/ Failure	Probable Cause	Casing Lost	Casing Diameter	Number of Wells
5	37.50	lo/78	Oil Fill	Anh. Slough	456'	9.625	3
5	38.65	08/88	Static	Salt Fall	204'	10.75	3
5	38.65	06/90	Static	Salt Fall	458'	10.75	3
SC	34.05	07/92	Static	Salt Fall	530'	9.625	3
101C	9.03	10/83	Leach/Fill	Salt Fall	226'	13.375	2
102B	6.04	07/83	Leach/Fill	Salt Fall	817'	13.375	2
102B	11.55	07/90	static	Salt Fall	747'	10.75	2
103C	2.66	10/82	Workover	Tbg. hung on lip cement csg.	4202'	13.375	2
103C	10.25	12/83	Workover	Csg. parted plg. in sand	3802'	13.375	2
103C	11.68	08/87	Static	Salt Fall	156'	13.375	2
103C	11.68	11/87	Static	Salt Fall	343'	10.375	2
103C	11.68	10/90	Static	Salt Fall	284'	10.75	2
105B	11.19	03/83	Oil Fill	Undrwt. csg./ brine in oil	2377'	13.375	2
106A	12.53	05/86	Depressure	Salt Fall	1027'	10.75	3
106C	12.25	01/88	Static	Salt Fall	3340' Dm	10.75	3
106A	12.53	07/90	Static	Salt Fall	3400' Dm	10.75	3
106A	12.53	03/91	Static	Salt Fall	1080'	10.75	3
106C	12.53	04/91	Static	Salt Fall	1238'	10.75	3
106A	12.45	05/92	Static	Salt Fall	561'	10.75	3
106C	12.45	05/92	Static	Salt Fall	431'	10.75	3
107C	11.50	08/84	Static	Salt Fall	1232'	10.75	3
107B	11.50	09/84	Static	Salt Fall	Damage	10.75	3
107A	11.50	06/86	Depressure	Salt Fall	297'	10.75	3
107A	11.53	04/89	Static	Salt Fall	3174'	10.75	3
107A	10.18	06/92	static	Salt Fall	1125'	10.75	3
107A	10.18	09/93	Workover	Salt Fall	@3500'	10.75	3
107C	10.18	09/93	Workover	Salt Fall	@3 100'	10.75	3
108A	9.28	04/84	Leach/Fill	Salt Fall	767'	10.75	3
108B	9.28	04/84	Leach/Fill	Salt Fall	41'	10.75	3
108B	12.24	01/87	static	Salt Fall	620'	10.75	3
109C	10.94	07/83	Leach/Fill	Salt Fall	97'	10.75	3
109B	11.60	11/84	Static	Salt Fall	305/	10.75	3
109A	11.62	11/87	Static	Salt Fall	268"	10.75	3
112A	11.21	08/85	Static	Salt Fall	769'	10.75	2
112A	11.07	12/86	Static	Salt Fall	1371'	10.75	2
112A	11.07	06/89	Static	Salt Fall	1304'	10.75	2
112A	11.07	11/90	Static	Poss.Salt Fl.	992'	10.75	2
112A	9.64	01/93	Static	Salt Fall	1563	10.75	2

[1] Hushang Bakhtiari, DynMcDermott: Cavern Engineering Report, 09 April 93; **Note:** "this list does not count casing cuts to reposition the string depth."

result in more presumed salt falls is unknown. Many have thought that three-well caverns created salt walls that were more conducive to falling salt, as fully two-thirds of the incidents occurred in them **(Table 4).** However, even if that is a causative factor, the remaining one-third of the incidents in two-well caverns is still excessive and anomalous with respect to the other SPR sites.

The possible association with anomalous zones is ambiguous, as is the correlation with gassy oil, discussed in the following section. Thorns (in Neal, et al., 1993) has plotted those caverns with salt falls; it reveals two discrete bands or zones separated by a central zone (consisting of Caverns 1, 2, 3, 4, 104, and 105) that is virtually devoid of salt falls, and relatively less gassy oil accumulation. This clustering suggests a possible geologic association, as patterns such as these could manifest a lobe or zone with specific properties. However, nothing of a geologic nature was recognizable that would suggest any associations involving the particular caverns identified in Table 3, but casing failures should be expected to continue preferentially in them. The economic penalty of continuing salt falls appears to provide the incentive for additional study of causative factors. A program to monitor pressure fluctuations that might indicate salt falls was being considered in mid- 1994.

<u>Gas in Oil</u>

In early 1993 it was learned that a number of caverns within the SPR system had excessive amounts of gaseous hydrocarbons dissolved in the oil. The oil would require degassing prior to refining in many cases, and because the processing rate may be less than the drawdown rate criteria, cycling of oil and concomitant degassing is anticipated in order to maintain readiness [Oil and Gas Journal, 1993, 19941.

In a number of instances the gas content had increased, leading to the conclusion that the source originated from within the salt [Hinkebein, et al., 19941. Gas in salt has long been a problem in conventional mining, leading to several fatal accidents following outbursts of gas and associated saltfalls [Molinda, 19881. At Bayou Choctaw, Caverns 18 and 20 showed higher than allowable gas content in March and May, 1993, and were identified as requiring treatment prior to drawdown. A possible correlation of gassy caverns and a N 750 E trending shear zone which transects the dome may exist; a similar N 45O W shear zone occurs at Bryan Mound [Thorns, 19931. The apparent corre-

Table 4 Correlation of Salt Falls with Numbers of Wells and Chimneys*

Cavern	# Wells	Salt Falls	# Chimneys	Remarks
101	2	1	2	
102	2	2	2	
103	2	3	2	anomalously high gas content
104	3	0	3	
105	2	0	2	
106	3	7	3	
107	3	7	3	
108	3	3	2	
109	3	3	2	
110	3	0	3	
111	2	0	1	anomalously high gas content
112	2	5	1	anomalously high gas content
113	2	0	1	
114	2	0	1	high gas content
115	2	0	1	
114	2	0	1	high gas content

Notes: **(1)** Cavern 5 excluded from statistics (leached with 1 well, then operated with 3)
(2) 5 salt falls damaged both strings at once, totalling 10 damaged strings

Summary of Table 4:

Of 31 Strings Damaged by Salt Falls:

14 occurred in the 4 caverns with 3 chimneys (14/4 = 3.5 per cavern)
12 occurred in the 6 caverns with 2 chimneys (12/6 = 2.0 per cavern)
5 occurred in the 6 caverns with 1 chimney (5/6 = 0.83 per cavern)

Better correlation with number of wells:

20 occurred in the 6 caverns with 3 wells (20/6 = 3.3 per cavern)
11 occurred in the 10 caverns with 2 wells (11/10 = 1.1 per cavern)
Two 3-well caverns had no salt falls

* This summary was provided by Ken Mills, DynMcDermott (1994)

lation with the *anomalous zone (AZ)* at Bayou Choctaw may be similar to that noted by Iannacchione et al. [19841 in his study of gas associated with salt outbursts in conventional mining. This correlation suggests that gas migrates through these AZs and into the adjacent salt at a faster rate than in normal salt. At Bayou Choctaw Caverns 18 and 20 are evidently in the salt adjacent to the AZ. As noted earlier, Cavern 20 is also located near the edge of the salt and adjacent to gas-producing sands. The rate of increase in gas content in these two caverns at Bayou Choctaw is uncertain.

At Bryan Mound there are ten caverns showing marginal to excessive gas in oil ratios, virtually half of the inventory. Six Caverns (2, 5, 103, 111, 112, 114, and 116), have the highest historical intrusion rates and are estimated to continue to have problematic intrusion rates in the future [Hinkebein et al., 19941. Three caverns, #s 5, 103, and 112, also have had a history of apparent salt falls and concomitant casing loss, which is discussed in the preceding section. The correlation of Bryan Mound caverns having excess gas with specific geologic features is uncertain, but some indications are evident and may be tested further in future studies. **Figure 2 (p. lo- 11)** shows the location of two intersecting anomalous zones, trending N45" W and N17%, the latter labeled as a *possible* AZ. The six caverns identified above , excepting #I 16, are all within a few hundred feet of these AZs at the surface, but the subsurface extent is not well understood. Cavern 116 is located near the periphery, similar to Bayou Choctaw Cavern 20 and that may be factor that facilitates greater gas intrusion, However, at least eight other cavems are equally as close to the AZs and do not contain similar excessive gas intrusion rates, thus ambiguity exists and this provisional correlation may have questionable validity. The concept of anomalous zones in salt domes has evolved over the past forty years or so and is based on a very limited number of observations, mostly within underground mines, and even then in only a few domes with limited area1 extent weal et al., 19931. For these reasons, the understanding of gas in salt may require substantial study to arrive at definitive origins.

3.2 Subsidence

Groundwater and/or oil withdrawal has created localized subsidence depressions around Houston and Freeport ranging up to nearly ten, and more than two feet, respectively [Gabrysch, 19821. Bryan Mound is on the western periphery of the Freeport subsidence bowl, which resulted largely from the pumping of ground water from municipal and industrial wells less than 500 feet deep. The depression could affect surrounding lowland areas and create flooding problems tit were to intensify. There has been no new subsidence data since the 1982 Gabrysch report in the Freeport area; it is outside of the areas of major concern in Harris (Houston) and Galveston counties. Neither subsidence nor groundwater measurements are anticipated in the future, according to United States Geological Survey personnel [Barbie, 19931. Significantly, Freeport stopped using groundwater for municipal supplies in 1988 [Shipp, 19931, relying entirely on surface water from the Brazosport Water Authority. As a result, the groundwater environment has again been altered and will fi.uther affect regional subsidence rates, if not curtailing them.

A consequence of the very intensive pumping of ground water in the greater Houston area has been subsidence and associated surface displacement along growth faults. Numerous small scarps of l-2 A in height have caused extensive damage to homes and businesses and required extensive repairs and/or demolition. The conversion fi-om ground to surface water as a source of municipal supply in East Houston has significantly reduced the subsidence and associated faulting, thus establishing a positive correlation between the two phenomena [Holzer and Gabrysch, 19871. The amount of subsidence in Freeport is substantially less than at Houston, and because of the cessation of ground water use for municipal and industrial use, is essentially arrested. Induced activation of growth faults such as in Houston appears much less likely to occur, but could be a problem affecting oil and/or brine pipeline integrity. Ground-water levels taken between 1968- 1989 in five municipal and industrial wells within the Freeport subsidence basin were examined and none showed declining water levels. This shows that withdrawals were being exceeded by recharge and that the subsidence depression was likely caused by pre-1968 water declines. Gabrysch [19931 reports that 1942 levels were substantially above depths of

50 A, confirming that the subsidence depression is largely a product of the *1940s* and *50s*

The Bryan Mound subsidence network has been tied to reference benchmark USC&GS 1274 at the corner of the Velasco Street Bridge in Freeport, using the same elevation in 1992 as was used in 1978 (16.96'). Because the Freeport subsidence basin may have been altered as groundwater continued to be extracted (until 1988), this benchmark, located near the center of the subsidence bowl, may also have been affected, but at the very least, is of questionable accuracy. The National Geodetic Survey (NGS) indicates they do not relevel these monuments routinely unless there is a major project or other reason to do so. Gabrysch [19931 points out there was an instrumental error (involving the Zeiss NI-1 level) that was experienced by the NGS in the 1970s. Consequently the data from Bryan Mound are likely invalid in an absolute sense, but they still may accurately show the relative subsidence effects between the land surface over the caverns and that in downtown Freeport. But any additional subsidence occurring over the Freeport subsidence bowl would be reflected in that measured over the caverns; thus an erroneous, lesser value of subsidence than actually is occurring may have been reported.

Survey data are somewhat inconclusive because of the very low rates, for the reasons explained above, and because the maximum allowable survey error (17.2 mm) is likely greater than the presumed subsidence. Virtually all of the stations show less than one-half of one foot total subsidence for a ten year period. However, McHenry [19921 cautions that the 1985- 1990 data are less accurate than more recent data. **Table 5** shows elevation change at selected subsidence stations. Of these stations the range is from 0.002 to .068 fi/yr (l-2 1 mm/yr), for an average of 0.036 fi/yr (11 mm/yr). The higher and lower values are sufficiently skewed from the other values so as to be questionable. There is also very little spread in the data from point to point , so that meaningfil patterns or contouring are impractical. The data in Table 4 excluded three previous surveys going back to 1982 which contained a presumed systematic error; however, there are no inconsistencies in either data set when a systematic correction is assumed.

A few conclusions can be reached, however tentative, based on these observations and the understanding of subsidence at other SPR sites: *The subsidence &a obtained at Bryan Mound between 1982 and I994 show very low overall averages; in fact they are the lowest of all the SPR sites.* A contradiction in the intuitive understanding

Table 5 Elevation Change at Selected Subsidence Stations, 1985-1994

Station	3/85	11/86	9/87	12/88	1/90	2/91	1/92	12/92	4/94	Δ	feet/year
6C	19.12	19.00	19.00	19.00	18.92	18.85	18.61	18.61	18.50	0.62	.068
7A	10.87	10.78	10.80	10.78	10.69.	10.63	10.56	10.51	10.48	0.39	.043
8B	10.82	10.84	10.84	10.88	10.83	10.74	10.66	10.62	10.58	0.24	,026
9C	8.94	8.84	8.87	8.89	8.81	8.74	8.69	8.62	8.59	0.35	.039
10A	8.78	8.69	8.72	8.71	8.64	8.58	8.49	8.46	8.43	0.35	.039
11A	23.77	23.72	23.72	23.73	23.71	23.65	23.55	23.58	23.51	0.26	.029
12c	NA	9.82	9.87	9.88	9.79	9.73	9.62	9.71	9.59	0.23	.031
13A	9.54	9.45	9.44	9.49	9.41	9.47	9.28	9.26	9.21	0.33	.036
BM2	16.95	16.92	16.85	16.83	16.79	16.71	16.67	16.63	16.52	0.43	.047
BM4	14.28	14.14	14.14	14.18	14.12	14.05	13.98	13.94	13.88	0.40	.044
BM5	7.55	7.46	7.46	7.51	7.44	7.38	7.33	7.31	7.24	0.31	.034
BM101C	6.53	6.40	6.44	6.51	6.45	6.73	6.34	6.34	6.26	0.27	.030
BM102C	6.11	6.06	6.09	6.13	6.11	6.06	6.01	5.98	5.94	0.17	.019
BM103C	6.52	6.44	6.48	6.56	6.52	6.49	6.42	6.43	6.39	0.13	.014
BM104C	10.29	10.22	10.22	10.26	10.19	10.13.	10.05	10.06	9.99	0.30	.033
BM105C	12.83	12.75	12.71	12.80	12.74	12.86	12.62	12.61	12.56	0.27	.030
BM106A	15.83	15.73	15.76	15.79	15.70	15.64	15.57	15.53	15.49	0.34	.037
BM107C	15.59	15.46	15.51	15.54	15.45	15.38	15.30	15.28	15.22	0.37	.041
BM108A	15.98	15.88	115.85	15.95	15.87	15.80	15.75	15.72	15.66	0.32	.035
BM109C	15.88	15.79	15.81	15.82	15.76	15.70	15.62	15.60	15.54	0.34	.037
BM110B	15.77	15.69	15.70	15.68	15.63	15.56	15.51	15.47	15.37	0.40	.044
BM111B	6.59	6.58	6.59	6.65	6.65	6.60	6.72	6.74	6.57	0.02	.002
BM112A	11.51	11.36	11.32	11.30	11.37	11.31	11.14	11.11	11.07	0.44	.048
BM113A	NA	NA	NA	NA	NA	NA	8.31	8.30	8.22	0.09	.040
BM114A	NA	NA	NA	NA	NA	NA	9.37	9.33	9.30	0.07	.031
BM115A	NA	NA	NA	NA	NA	NA	11.24	11.21	11.16	0.08	.036
BM116A	NA	NA	NA	NA	NA	NA	7.31	7.27	7.23	0.08	.036
SMS1	8.55	NA	8.50	8.49	8.45	8.39	8.32	8.29	8.23	0.32	.035
SMS5	15.82	NA	15.72	15.70	15.65	15.59	15.53	15.48	15.42	0.40	.044
SMS9	11.59	NA	11.47	11.51	11.44	11.37	11.30	11.28	11.22	0.37	.041
SMS10	11.79	NA	11.86	11.89	11.84	11.78	11.71	NA	11.63	0.16	.018
SMS12	9.15	NA	9.04	9.08	9.01	8.95	8.88	8.87	8.80	0.35	.039
SMS13	11.11	11.00	11.00	11.03	10.96	10.90	10.84	10.80	10.74	0.37	.041
SMS19	6.51	6.44	6.46	6.50	6.44	6.38	6.29	6.30	6.23	0.28	.031
SMS20	8.83	8.75	8.76	8.80	8.73	8.67	8.61	8.59	8.51	0.32	.035
SMS25	8.86	8.75	8.78	8.79	8.74	8.68	8.58	8.58	8.52	0.34	.037
SMS28	7.84	7.73	7.75	7.80	7.72	7.66	7.60	7.55	7.52	0.32	.035
SMS29	10.43	10.33	10.30	10.36	10.30	10.24	10.18	10.15	10.09	0.34	.037
SMS31	6.32	6.24	6.23	6.30	6.23	6.17	6.11	6.11	6.04	0.28	.031
											Σ = 14.08

Average = .036 ft/yr (11 mm/yr)

NA = data not available

Note: Stations 6C and 111B are sufficiently skewed from other values so as to be questionable of subsidence exists, considering that Bryan Mound has the largest cavern volume of all the sites; thus greater cavern creep closure might be expected. For example, West Hackberry has the highest rate, some eight times that at Bryan Mound, and with an equivalent (although slightly higher) total cavern volume for the whole dome. The possible cause of this disparity may lie in much lower salt creep rates in Bryan Mound salt [Wawersik and Zeuch, 1984] and in the somewhat deeper caverns at West Hackberry [Neal, 1991].

Subsidence effects related to the size of the dome were modeled by Hoffman and Ehgartner [1993], using a 3-D finite element model of a 7-Cavern storage field similar in geometry to SPR caverns. Dome diameters of 2.0, 1 .0, and 0.5 miles were examined, and corresponding volume losses of 5.2, 3.9, and 2.5 percent were predicted for the relatively small 7-cavern facility at 30 yrs, respectively. A larger cavern field, such as at Bryan Mound, would also experience decreases in storage losses as the dome diameter decreases. In comparison to West Hackberry (dome diameter greater than 2 miles), the storage losses at Bryan Mound (dome diameter approximately one mile) should be significantly less because of its smaller dome size and harder salt (slower creep rate). This hypothesis could be tested by relative comparisons of deep survey monuments tied to salt.

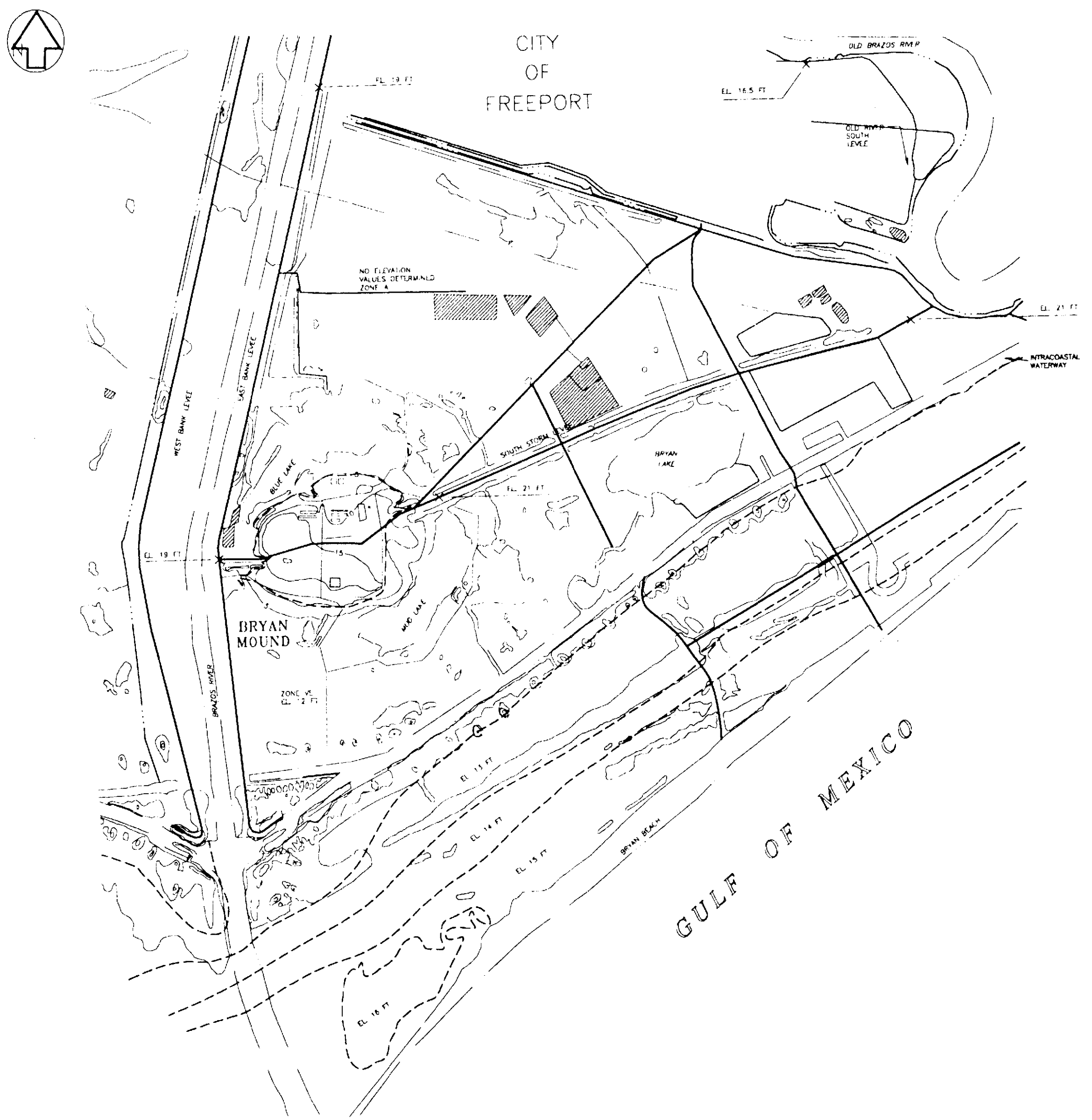
The most serious effect of subsidence near coastal areas, and in particular at Bryan Mound, is additional loss of already low elevation, which makes the susceptibility to hurricane surge a greater threat. Because of the apparent very low subsidence rates occurring at Bryan Mound, and because the local subsidence caused by excessive ground water pumping has largely been curtailed, subsidence is not an issue of significance at this time. However, because of the uncertainties cited above, continuing surveillance is essential.

3.3 Flooding

There is little that is new which would significantly change the 1980 evaluation of flood conditions at Bryan Mound. Subsidence has been sufficiently low so that site vulnerability has not changed appreciably, even though the location is very near the coast. The major flood threat is from overland surge during hurricanes and that threat model has not changed. Calculations by the Corps of Engineers suggest that surge heights of 10 ft can be expected along the coast 2.5 times per 100 years and that maximum surge height is 13 ft [Bodine, 1969]. However, the estimated change in water surge elevation between the coast and the Bryan Mound site was five feet, recorded during what was estimated to be a near- 100 yr event (the August, 1915 hurricane). Thus, according to this data and for that kind of event, the high-water mark during extreme storm events is apt to be less than 10 A, and as low as 8 ft above mean sea level for the 100 yr event. The values for 500 yr flood events are typically only slightly higher than 100 yr events. The FEMA estimates, reproduced in **(Figure 15)**, show a 3 ft drop in elevation from 15 to 12 feet between the coast and a location between the Intracoastal Waterway and Bryan Mound during a 100 yr event. This information, along with a maximum coastal water elevation of 14 ft (presumably a conservative upper value), would translate to a predicted high water elevation at Bryan Mound in the 10-12 A range. In addition, wave crests could add to this maximum elevation range.

During the 1961 Hurricane Carla, also considered to be a near-l 00 yr event, the highest recorded surge elevation along the Texas coast was 12.3 ft, near Freeport. Minimum dike heights for the Bryan Mound area are 17.5 A and the dike passes through the site, taking advantage of the higher elevations on the dome. This higher elevation and the flood levee would protect much of the dome during 500 yr flood events (from hurricane surges; **see Figure 15).** However, this still leaves 11 caverns (with aggregate storage volume exceeding 100 MMBBL) south of the protection levee, so that temporary flooding can be anticipated during hurricanes that have significant overland surge. As a consequence, temporary shutdowns must be anticipated.

As part of the FEMA Flood Insurance Study for Brazoria County [FEMA, 1993], a frequency analysis showed computed flood elevations and tidal surge heights (stillwater elevations) associated with various return-period storm events. This analysis predicted the following stillwater elevations in the Bryan Mound area:



LEGEND

- LEVEES
- X SPOT ELEVATIONS
- ○ AREA AT BRYAN MOUND SAFE FROM 500 YEAR FLOOD EVENT (FEMA)
- - - 100 YEAR COASTAL FLOOD WITH VELOCITY (WAVE) HAZARD; BASE FLOOD ELEVATIONS DETERMINED SOUTH OF SOUTH STORM LEVEE ONLY (ZONE VE, FEMA)

0 4000 8000
SCALE
FEET

ACRES

SANDIA NATIONAL LABORATORIES

BRYAN MOUND SALT DOME

FLOOD ZONE MAP FROM
REVISED FEMA ANALYSIS, 1993

CONSULTANT
DR. T. R. MAGORIAN

ACRES INTERNATIONAL CORPORATION - FEB 1994

FIGURE 15

RAK 5/20/94 PC788413
FILE DRG045 ...

Return Period, Years	Stillwater Elevation, Feet
10	5-5.5
50	8.9-9.8
100	10.0-l 1 .o
500	12.1-13.1

The FEMA flood insurance zones around Bryan Mound show the area south of the South Storm Levee classified as Zone VE, characterized as 100-yr coastal flood plain having additional storm-wave hazards. Whole-foot base flood elevations derived from the FEMA analysis are shown on Figure XX. The area north of the South Storm Levee is classified as Zone A, indicating that base flood elevations have not been determined.

Speculation on increased hurricane frequency was rampant following the summer 1992 occurrence of three major hurricanes in 19 days affecting the United States and its territories. There is lack of agreement on cyclical trends, but there is general agreement among atmospheric physicists that warmer oceans will increase severity of tropical storms, and probably the frequency [Emanuel, 1988]. Thus, understanding of greenhouse warming trends, *if real*, has implications on tropical storm generation, and consequent flooding effects. Should hurricane trend changes be noted, flood frequency determinations will need to be reexamined.

3.3.1 Projected Loss of Coastal Shorelines

Whereas Louisiana has undergone continuing, progressive loss of its coastal marshlands in this century, Texas is far less vulnerable in this regard, experiencing nowhere near the rate of loss [Morton and Pieper, 1975; Paine and Morton, 1989]. Surface elevations, sediment types, and geologic conditions are generally more favorable with respect to coastal erosion than in Louisiana, but are apparently highest in Texas just west of Freeport. Measurements of coastal retreat adjacent to Bryan Mound are very low, on the order of 15 ft per year. Measurements west of the New Brazos River by the Army Corps of Engineers [Tanner, 1991] near Sargent (15 miles west of Bryan Mound) showed rates of 30 A / yr, which would be about a kilometer / century. Subsidence rates in this vicinity are also very low. The Corps of Engineers is currently planning a massive concrete structure along some 10 miles of the Intracoastal Waterway in this vicinity, and has as its goal to preserve the integrity of all land north of the Intracoastal. There has not been a need perceived for such works of engineering in the immediate vicinity of Bryan Mound.

Paine and Morton [1989] reported that shoreline near the Freeport jetties just east of Bryan Beach retreated more slowly than shoreline near the new Brazos delta, despite the Brazos discharge. Retreat rates near the Freeport Jetties were slower between 1956 and 1974 than between 1930 and 1956 and continued to decline between 1974 and 1982, ranging from 3.1 to 9.7 ft/yr as the shoreline became more linear. Just three miles southwest of the new Brazos River, the San Bernard River flows into the Gulf and is rapidly prograding new delta at rates exceeding 100 R/year

These historical shoreline data show that the Bryan Beach area is stable at this time and is probably experiencing very slow, if any, shoreline loss at this time. Thus, the Bryan Mound dome is unaffected by any threat of shoreline erosion.

3.4 Seismicity

The 1980 site characterization report [Hogan et al., 1980] noted that nearly all of the faults defined on the Texas Gulf Plain are “growth” faults, which generally are considered to be aseismic. That is, they are not in the same class of faults that originate in deep-seated tectonic processes, but rather result from gravity sliding. In Houston, many growth faults have shown reactivation during the 1960’s and 70's, presumably as a consequence of intensive ground water withdrawal and associated subsidence [Davis et al., 1989; Verbeek, E. R., 1979]. The motion on these faults is essentially aseismic, and surface displacements occur as a result of gradual creep of subsurface sediments, rather than sudden strain release normally associated with earthquakes, The potential for the reactivation of movement along growth faults in the Freeport area has been considered and is discussed in the section on subsidence (3.2); it is not anticipated to be an issue of significance. However, should faulting occur, it could affect the integrity of oil or brine pipelines and possibly some surface facilities.

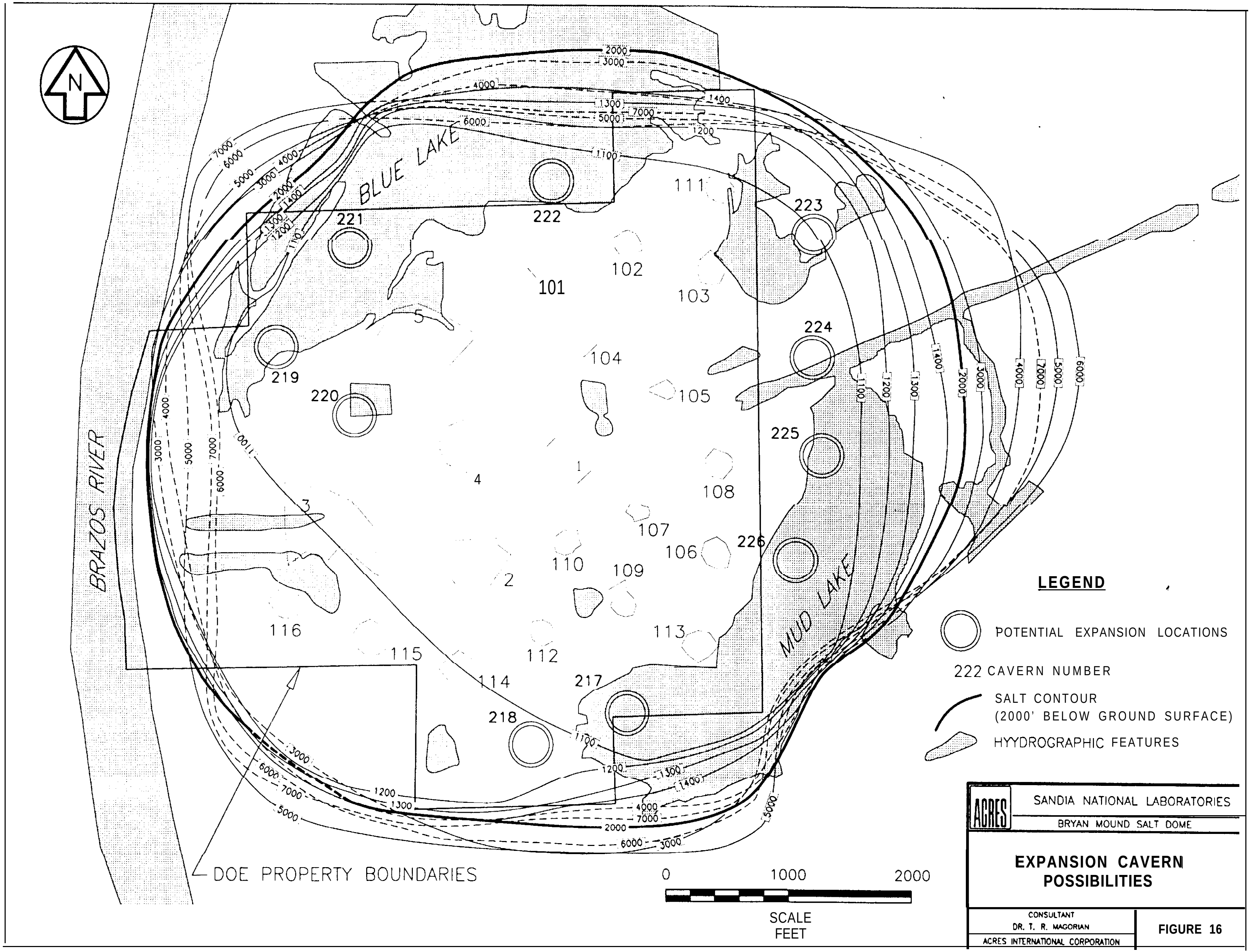
Based largely on studies for the South Texas Nuclear Plant located near Bay City, 40 miles west of Bryan Mound, the maximum credible earthquake was assigned a Modified Mercalli intensity of VI, which translates to an acceleration of approximately 0.07g at the site. This value is very similar to peak accelerations experienced near the epicenter during the 19 Oct 30 Donaldsonville, LA, event, epicentered 40 mi southest of the Bayou Choctaw site, and which effectively has become the design basis earthquake for the Gulf Coast. The basic conclusions reached in the 1980 Bryan Mound study remain valid; only minor refinements are offered in **Appendix B** to update the understanding of seismic risk. The additional possibility, although remote, of induced seismicity from injection wells is also addressed.

3.5 Expansion Cavern Possibilities

Currently there is no SPR requirement to identify additional cavern locations, but future situations conceivably could necessitate that. Such an eventuality is briefly addressed, not withstanding the surface problems that would have to be addressed — such as low elevation and standing water in Blue and Mud Lakes.

The principal limiting criteria for additional cavern space is the amount of available salt beyond existing caverns and around the dome periphery. This determination invokes major uncertainty because of the small number of wells and other data. The 300 ft buffer distance between the outside cavern wall and dome edge is a minimum; 500 A is thought to be better, as salt conditions usually are less pure and physical properties are often deteriorating as the edge is approached. A summary of the external dome features is shown in **Table 6.**

There may be space for one or two 10 MMB caverns south of Cavern 114 and/or Cavern 109 along the southern perimeter of the dome (locations #217, #2 **18; (Figure 16).** Location #217 is in Mud Lake and would require protective diking, similar to Cavern 113. A small overhang occurs on the southern side of the dome and an exploratory borehole might be required to validate this location. The present surface elevation of <5 ft is a siting factor having potential operational ramifications, but probably of no more concern than other low-lying parts of the site. Regardless of location on the dome, the SPR site needs hurricane protection.


N
BRAZOS RIVER
BLUE LAKE
MUD LAKE
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103
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1
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DOE PROPERTY BOUNDARIES
0 1000 2000
SCALE
FEET
LEGEND
POTENTIAL EXPANSION LOCATIONS
222 CAVERN NUMBER
SALT CONTOUR
(2000' BELOW GROUND SURFACE)
HYYDROGRAPHIC FEATURES
ACRES
SANDIA NATIONAL LABORATORIES
BRYAN MOUND SALT DOME
EXPANSION CAVERN
POSSIBILITIES
CONSULTANT
DR. T. R. MAGORIAN
ACRES INTERNATIONAL CORPORATION
FIGURE 16

Table 6 Additional Storage Possibilities (from Interpreted Geologic Sections)

Flank	Potential	Remarks
SE	OK	Sediment convergence shows vertical salt wall
NW	Questionable*	Assumed || to SE geometry; deep overhang from 1949 seismic survey unlikely'
N	Questionable*	No well control, even from convergence extrapolation
SW	OK	Well defined shallow overhang
NE/E	OK	Bulge, shale sheath; assume overhang below 5000 ft
S	OK	Probable shallow overhang
W	OK	Wide shale sheath below AB unconformity

*Principal discrepancy: Modem seismic profiling required. + The wide shale sheath found since the previous characterization makes this location relatively safe.

A second 10 MMB cavern location (#223) has been suggested on the east side of the dome, northeast of Cavern 103 and off of DOE property. This location is also <5 A above sea level. A confirmatory borehole would establish the dome configuration and validate the suitability of this location. Locations south of here and east of the DOE property are also possibilities for two or three additional caverns.

Locations on the west and northwest perimeter of the dome (#s 2 19, 22 1, 222) might be considered but have more uncertainty and exploratory boreholes or additional geophysics are needed to validate the dome geometry. That is because the seismic data on which these overhangs were interpreted are unreliable, probably having been exaggerated in the interest of economic promotion. The low-lying elevation must also be considered; all three are in or very close to Blue Lake and reclamation/diking would be necessary. Additional property acquisition would be required for locations #222, 223, and those south of 223 (224-226).

Cavern 3, plugged and abandoned, is pancake-shaped and considerably more shallow than DOE Phase III caverns; room for a deeper cavern (#220) under Cavern 3 is a possibility, but integrity evaluation would be required. A similar location west and under Cavern 3 is also possible but requires evaluation.

Assuming the above concerns can be reconciled, Bryan Mound most likely has under Cavern 3 is also possible but requires evaluation.

Assuming the above concerns can be reconciled, Bryan Mound most likely has space for at least three additional 10 MMB caverns, and very probably three others for a total of 60 MMB, and possibly more, but only with confirmatory exploration. This assumes that mitigative work to overcome the low elevations and water-based sites could be accomplished readily.

4 SUMMARY OF SIGNIFICANT FINDINGS AFFECTING SPR

Refinements to the original (1980) geological characterization have been made; those topics most relevant to operations are identified and summarized as follows:

- **Salt stock shape** is quite cylindrical, with steep overhangs on the north, east, and south sides, and a localized bulge (nose) on the east. The northwest overhang identified in the 1980 report is probably not present, as interpreted from the gravity contours and limited well control. The new interpretation, although requiring verification, would allow for as many as six new caverns of 10 million barrel size. Some of these locations underlie Blue and Mud Lakes on the site periphery.

- **Structural features** include radial faults external to the dome and two probable anomalous zones transecting the salt stock and dividing it into four separate lobes or spines. These structural features probably control permeability zones within the salt and may account for the differential release of gas from salt into the oil, but this has not been definitively established

- Presumed **salt falls** have been a persistent, recurring problem in ten separate caverns with some 37 incidents occurring over a ten-year period. While the cavems involved are clustered together in two areas and suggest some possible excessive intrusion in the future. A satisfactory geological explanation for this differential expression is not evident.

- **Subsidence** is the lowest of all the SPR sites, even though the volume is large, comparable with West Hackberry, which has a subsidence rate some six or seven times greater. The explanation appears to lie in slower laboratory creep for Bryan Mound salt and in slightly deeper caverns at West Hackberry, which leads to increased cavern creep closure.

- **Flooding risks** are virtually unchanged with respect to the SPR site, however minor revisions have been made in the most recent FEMA analyses regarding the surrounding region. 100-year flood elevations from hurricane surge can be expected to temporarily flood low-lying elevations under 1 O.O- 11 .O feet. Shorelines at Bryan Beach are considered stable and will not recede appreciably in coming decades.

- Bryan Mound is in a **seismically quiescent** portion of the Gulf Coast. Although minor earthquakes are expected to occur periodically, such as the Oct 83 West Hackberry temblor (M = 3 .8), the maximum intensity is estimated to be very low (Modified Mercalli = VI), and virtually no damage of consequence will occur.

- This characterization update should be reevaluated periodically for currency and reaccomplished in not more than ten years.

5 ACKNOWLEDGMENTS

This effort to reevaluate the Bryan Mound geological characterization has been made easier by the splendid cooperation and assistance from many colleagues: Stu Thompson at Acres International Corporation, Bob Thorns of AGM Inc., Ken Mills of the DynMcDermott Petroleum Operations Company, and Steve Bauer, Marianne Walck, and Brian Ehgartner of Sandia National Laboratories, who reviewed all or portions of the report and made many suggestions for improvement. We also thank Sam Wallace and Fran Grosshans at Sandia for the many hours of help in which they assisted in the myriad of small tasks necessary to produce such a report.

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APPENDICES

A Regional Geology

B Seismicity and Faulting Potential

C Bryan Mound Well Data

D Selected Core and Thin Section Photographs

APPENDIX A

Bryan Mound Regional Geologic History

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Bryan Mound Regional Geologic History

Introduction

This overview is intended for readers that desire general information, and for those having limited background in the geosciences. It is not detailed, and is uneven in presentation by design. The reader who desires more complete information should refer to the original characterization report [Hogan et al., main report], or to more recent general references on Gulf Coast geology and tectonics [Worrall and Snelson, 1989].

Paleozoic Era (570-245 my)

The single protocontinent called Pangaea ("all lands") that drifted together at the end of the Paleozoic, resulted in a huge mountain mass, probably somewhat like the Himalayas today. It lay to the north (relative to today), including the center of North America, and is thought to have been glaciated periodically, tying up much ocean water in icefields.

No rocks of Paleozoic age are expected to underlie the site, as the nearest known exposures are of Bend turbidites on the Colorado River above Austin, TX, some 190 mi to the northwest. Metamorphosed Paleozoic schist extends eastward from Bell County, TX, just north of the Angelina-Caldwell flexure, which marks the south end of the Sabine Uplift separating the East Texas Salt Dome Basin from the North Louisiana Salt Dome Basin. Although little of this schist has been dated in Texas, it is equivalent to the Wissahickon schist of the East Coast Piedmont, known to be primarily of Cambro-Ordovician age, Southeast of the ridge, Mesozoic rocks may have been deposited on oceanic basalt crust of the edge of the continental shelf of the time.

Mesozoic Era (245-66 my)

The immense mass of the Paleozoic mountains led to the deformation and breakup of Pangaea during Jurassic time, initiating the Gulf of Mexico Basin and in the process forming volcanic rifts, similar to the African rift valleys and Red Sea today. The Gulf Coast Geosyncline, or major depositional basin, was one of a string of rift basins created by the opening of the Atlantic during the breakup of Pangaea. This process separated North America from South America and Africa, forming the Gulf of Mexico and the central Atlantic concurrently. This drifting apart of the present continents continues at a more or less steady rate, as it has since the end of the Paleozoic.

<u>Triassic Period:</u> Any basalt which is found under the site could be as old as Triassic and associated with the redbeds found in these deposits in both the East Coast and the Western United States. These are the oldest deposits of the Mid-Atlantic rift system which has carried the North American continental plate away from Africa and Europe and forms the active volcanoes of Iceland and the Azores. Triassic Eagle Mills basalts and redbeds are known in the subsurface of East Texas and North Louisiana.

Jurassic Period: The desert redbeds of early Jurassic age overlying the Triassic volcanics are called Norphlet in the Gulf Coast. The rift-valley depositional basin of the Jurassic Louann salt and evaporites, which underlies the Norphlet, was similar to some extension evaporite basins in East Africa and the Red Sea today. For the East Texas Province, Jackson and Seni [1984] estimated the original thickness of the Louann salt to be 5,000 to 7000 ft, although only 3000 A has been drilled. Two separate evaporite basins rifted apart: a northern region consisting of the coastal plain and off-shore regions Texas, Mexico, Louisiana, Mississippi, Florida and southern Arkansas; and a southern belt along the west and northwest flank of the Yucatan Peninsula. The present-day thickness and distribution of the "mother salt" is different than its original position as tilting of both basins has caused the migration of salt structures at depth, according to modern geological concepts.

Major changes in sea level and global temperatures provided widespread conditions for organic growth and preservation. The sealing anhydrite overlying the Triassic volcanics is called Buckner. The overlying oolite and dolomite is known as Smackover, the Gulf Coast correlative of the Arab limestone pay of the Persian Gulf, the most oil-productive horizon in the world. The remainder of the overlying Jurassic consists of a thick sequence of Cotton Valley limestone and Bossier bituminous shale. Although the salt in the Bryan Mound dome is of Jurassic age, it may have been deposited to the north or northwest, so that only oceanic basalts of this age or even younger were ever deposited here. None of these Jurassic rocks other than the salt have yet been drilled at Bryan Mound.

The salt from which the Bryan Mound salt dome formed is probably not in its original depositional position. It may have migrated southward and upward as a sill through the sediments described above or outside, seaward of the thick sediment wedge at a depth of two or three to six or seven miles. This sill is believed to be exposed at the toe of the sediment pile on the floor of the Sigsbee Deep, the oceanic trough in the Gulf of Mexico.

Continental rafting and seafloor spreading have revolutionized the concept of the origin of basins like the Gulf Coast Geosyncline; this current concept of deep horizontal salt migration and intrusion discussed here is one of the most innovative and important ideas today affecting hydrocarbon and salt development.

Cretaceous Period: The sequence of rocks found updip (inland of Bryan Mound) consists of the lower or Comanche age Hosston clastics and limes, Sligo oolitic limestone, Pine Island shale, the James lime reef covered by Ferry Lake anhydrite and Glen Rose limestone, forming a thick reef like Florida and the Bahamas. Bryan Mound is probably seaward of the reef front. This is all overlain unconformably by the almost-global upper Cretaceous Chalk section: called Austin, Taylor, and Navarro in Texas.

The chalk probably underlies the site in normal position, and may underlie the salt sill and thereby contain producible oil and gas --

which DOE has acquired along with the salt. But even these rocks have never been penetrated along the coast

Cenozoic Era (66-2 my)

Tertiary Period: The downdip surface section of the Gulf Coast proper in Louisiana and Texas is a thick pile of Tertiary sands and shales, correlative with the carbonates of Florida and the Bahamas. All of these deposits face the active east-west tectonic zone running from the Mexican volcanoes through the greater Antilles from Cuba to the Virgin Islands.

Paleocene Epoch: The Tertiary sequence of the Gulf Coast starts with Midway shale, a normal marine mud deposit washed west from the Mississippi (or equivalent) Delta . This sedimentation preceded the Laramide orogeny, the plate collision that created the Rocky Mountains and flooded the Gulf with coarse clastic debris. Based on the reconstruction of the regional geology, the ocean floor here was certainly solidified in place here by the end of the Cretaceous, so that it seems reasonably certain that a full, marine Tertiary section underlies the site.

Eocene Epoch: These are the oldest sediments deposited in the Gulf Coast delta sequence. As sediments accumulate on the north shore of the Gulf of Mexico, the older sediments are depressed and compacted, increasing their dip toward the Gulf Ultimately, a thick sedimentary section accumulated on the edge of the continent, referred to as the Gulf Coast Geosyncline. This simple regional picture is complicated by the instability of the underlying salt which formed more than 550 domes, all arising indirectly from the "mother salt", the Louann, found at depths of 30,000-40,000 ft in the Bryan Mound area.

Wilcox deltaic deposits as much as two miles thick, including coal measures which have been penetrated updip from the coast in Jefferson County, Texas, to the Rio Grande, represent the Laramide deposits. These are overlain by downdip Yegua shales which in turn are overlain by Jackson shale, part of the shallowest mature bituminous shale sequence of the Gulf Coast. The upper part of the bituminous sequence is the Vicksburg limy shale, of lower Oligocene age penetrated in the shale sheath in many domes However, none of these deposits have been penetrated yet at Bryan Mound and it appears that the Wilcox delta may not extend as far down dip as the coast at Bryan Mound.

Oligocene Epoch: The deep tests drilled by Humble (FSC #6, SW flank) and Houston Oil and Minerals (FSC #1, NW flank) appear to have been targeted at Frio sands, which are an important production zone at Peach Point, 8 mi northwest of the dome and at other salt domes such as Stratton Ridge, 7 mi northeast of Bryan Mound. The Frio formation is a thick marine sequence of sediments increasing in thickness from shoreline sands near the outcrop area in Frio County, TX, to deeper-water deposits of predominant geopressured shales and lesser turbidite sands near Bryan Mound. Wells drilled on the northwest flank of the dome were presumably targeted at the distal edge of turbidite sands such as those which produced at Peach Point. However, virtually no sand was found. **Table 1** lists principal stratigraphic horizons important to the geological interpretation.

The Anahuac Formation of Upper Oligocene is represented in thick shale units in all deeper wells and sheaths the dome; it is more than ten thousand feet thick in some wells in the vicinity. It contains at least two paleontological markers, from Discorbis and Heterostegina through Marginulina howei. At Damon Mound, some 35 mi north, and Stratton Ridge, seven miles northeast, the Heterostegina zone consists of thick coral reefs (atolls), but at Bryan Mound the Anahuac is a relatively continuous deep-water

Table 1 Bryan Mound Stratigraphic Correlation Chart

Unit	Symbol	Lithology
Holocene		alluvium
Pleistocene		
Beaumont		marine clay
Lissie		
Montgomery	**MO**	sand
Bentley	**LS** (lower Lissie)	mud
Lafayette		sand and gravel
Pliocene	**PL**	sand and mud
Miocene	**MI**	
Goliad		sand **(Bigenerina A)**
		shale
		sand (Bigenerina B)
		shale
		sand (Textularia L)
		shale
		sand **(Bigenerina 2)**
		shale
- - - - UNCONFORMITY	**Bigenerina humblei - - -**	UNCONFORMITY
		sand **(Cristellaria I)**
		shale
		sand **(Cibicides opima)**
Lagarto	**AB**	shale
Oakville	RL	deltaic sands
Oligocene		
Anahuac	**DR**	shale
Frio	**F**	geopressured shale* and turbidite sand

***P** on cross-sections **(Figures 8-11)** indicates geopressure, marked by reduced resistivity shale, containing relatively more volcanic ash than the overlying Miocene shales. The Anahuac at Bryan Mound is more than 11,000 ft thick and over-pressured, separating any possible deeper Frio pays from the overlying Miocene sand pile.

Three dramatic angular unconformities on this dome occur at the top of the Anahuac (basal Goliad, Lagarto, A & B, and Pliocene). The underlying Frio sands were uplifted and eroded by salt movement before Miocene deposition. This basal Miocene unconformity is one of three in the geologic history of the dome. The erosion occurred in the interval in which Heterostegina coral reefs developed to the east, including the atoll surrounding Bayou Choctaw, Stratton Ridge, Damon Mound, and many other domes. The alluvial Miocene sands lie across dipping and eroded Oligocene Oligocene Frio sands at angles of 65 degrees and probably higher from the horizontal. Here the angular unconformity is underlain by geopressured shale sheath, on which the normally-pressured Miocene sands lie in angular unconformity.

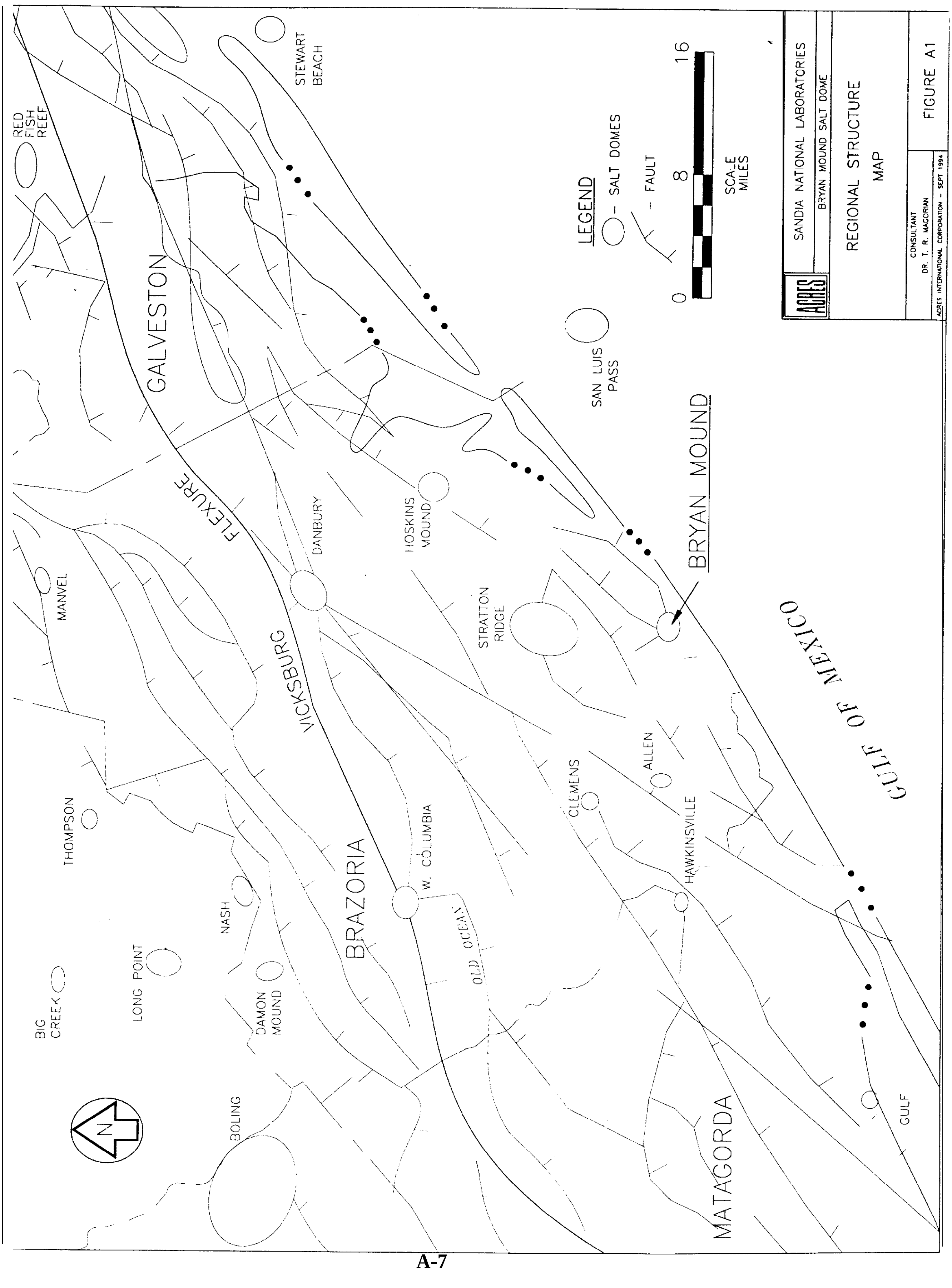
Another possible unconformity occurred in the middle of the Miocene at the top of the Lagarto Shale, under the Goliad sands (as now correlated with the updip outcrop). A final unconformity occurs at the top of the Miocene. Underlying Goliad beds may be very steep on the northwest side of the dome.

The top of the Anahuac shale is mapped **(Figure 7, main body of report)** to show the depth of an additional impermeable sheath around the dome, which can serve to provide a barrier in the unlikely event that a cavern were inadvertently leached through salt. This sheath, consisting of light volcanic-ash-rich mud forms a mobile sheath at geopressure around most of the salt stock below 3000 ft. This horizon is also best known from oil wells drilled on the flanks, so that these maps best reflect the control used in the subsurface study.

The linear down-to-the-coast growth faults (listric normal faults) of the middle Texas coast coalesce along the Vicksburg Flexure (shown as a bold line on the regional map), which approximately bounds the geopressured Anahuac shale, as well as being the updip margin of Vicksburg production. To the east, it intersects the edge of the Hackberry Embayment which include Big Hill and West Hackberry SPR sites **(Figure A-l).**

Miocene Epoch: Recent work by the Texas Bureau of Economic Geology has clarified the divisions of the Miocene in Texas between the outcrop and the subsurface [Galloway, 1986]. The lower Miocene deltaic sand sequence, originally used for brine disposal at Bryan Mound, is now correlated with the Oakville sands of the Live Oak County outcrop. The Middle Miocene shale of Amphistegina B age is now correlated with the Lagarto of the South Texas outcrop. The thick upper Miocene sandy sequence is now called Goliad. These sediments, which are productive of gas immediately offshore and of the small quantity of oil found on the south side overhang of the Bryan Mound salt stock, actually flank the storage in the salt above 3000 feet.

The outer edge of the shelf grew southward by several stages of deltaic progradation in lower Miocene time, so that the



RAK 09/06/94 P0798413

Anahuac shale is overlain by a clastic wedge, ranging from less than 2000 A thick on the coastal plain to more than 10,000 ft offshore. This thick sediment pile being dumped off the south edge of the North American continent at least since the Miocene is responsible for deforming the underlying Jurassic salt into ridges and domes. The intense loading by Miocene sediments activated many of growth faults associated with the shelf edge. Dips in these sands are limited to 30 degrees, even against the near-vertical salt face, except possibly at the northwest corner of the dome.

The base of the sand pile is paleontologically marked by the disappearance of Discorbis "restricted," the last far-offshore deposit in the stratigraphic sequence. The rest of the lower Miocene is represented by thick alluvial sands, the Oakville Formation, becoming more shaly with decreasing depth. The lower part has marine shale breaks including Siphonina davisi, correlated on some logs, and the Amphistegina zone unconformity. The predominantly sandy lower portions are suitable as brine disposal zones.

The middle Miocene is represented by the last marine shale breaks, particularly those containing the Amphistegina B fauna with volcanic ash from the Mexican orogeny. This is the shallowest paleontologic data point available around the dome, the upper Miocene being less marine. Table 1, the stratigraphic correlation chart, shows younger zones by their standard paleontological name, even though the marker microfossil is rare in these mostly non-marine sediments at Bryan Mound. These units have been correlated around the dome but have no other recognized name.

The middle Miocene is represented by the Lagarto shale, which also contains a few thin, relatively variable sands, Cibicicdes optima to the Bigenerina howei unconformity.

The alluvial section continues through the upper Miocene and into the Plio-Pleistocene and is now called the Goliad Formation in Texas, representing ancestral riverine deposits of present rivers. The basal unit is gravelly, resting unconformably on the marine Miocene. The Goliad consists of a series of "dirty" point-bar gravels, each some 100 ft thick, approximately the same as the natural flood channel of the Brazos River. The Goliad has the most extensive permeability (although not high) of any fully-saline sand and gravel on the Brazos-Colorado Delta; this is significant because of its potential for brine injection wells at the SPR site. These low permeability bars are overlain by cleaner reworked sands, silts and muds, some reasonably permeable. This unconformity below the gravel is eroded deeply into the middle Miocene close to the dome, indicating the dome had extensive surface expression during this onshore alluvial deposition.

Pliocene Epoch: These sediments are mostly back-bay clay shales with a few deltaic sand sequences, with brine disposal potential, and a few thin limy zones. (See Section 2.1, main body of report.)

Quaternary Period (<2my)

Pleistocene Epoch: The basal preglacial unconsolidated Lafayette gravels (also called Willis, Williana, and Citronelle locally) erode into the underlying Pliocene; it is thin and shallow at Bryan Mound. The overlying sediments are fresh-water bearing and were deposited during and after each of the glaciations of the continent to the north, when sea level was as much as 460 ft lower than today, and in the following interglacial stages as the sea returned to near its present level. Thus the basal sand of each sedimentary sequence, outwash brought down to the Gulf, is correlated with the glacial stage and the overlying mud with the following interglacial. Some or all of the glacial stage is actually represented by the basal unconformity below each channel sand [Ref. A-21.

Nebraskan Stage: The oldest glacial sequence is Nebraskan, found at the top of or just above the Lafayette (Willis) gravel. The overlying Aftonian mud contains a distinctive volcanic ash marker like those of the middle Miocene, which has been tied to the volcanic or orogenic theory of glaciation.

Kansan Stage: The Kansan, here mostly marine, is the Lenticulina sand, on the flanks of the dome. The Yarmouthian Angulogenerina clay, which represents the long interglacial interval in the middle of the Pleistocene, is called Bentley (or lower Lissie) and is found at 500 A over the top of the dome. It contains the uppermost glauconite marker in the sedimentary section, indicative along with the microfauna, of the most recent open marine sedimentation.

Illinoian Stage: Montgomery (or Upper Lissie) Trimosina sands, at 300 ft over the top of the dome, were deposited during the following glaciation. Sangamon clay was deposited during the following interglacial interval.

Wisconsin Stage: The Beaumont outwash sands of which the basal [Alton], at a depth of 200 A on top of the dome and 400 ft on the flanks, is the thickest and most massive, having been correlated over almost every onshore salt dome. At the surface to the northwest, they make up the plain which runs from Beaumont through Wharton to the Rio Grande.

The sands were formed at the lower sea level which occurring when the continental icecap extended to the Ohio and Missouri Rivers. The main sediment sources for the Texas Gulf Coast is the Brazos-Colorado Delta. Most of the sands are alluvial point bars with basal gravels, along with beach sand where the delta front is washed away by hurricanes.. Away from the structural influence of the dome, these sands dip toward the Gulf at the rate of 30 A per mile.

These unconsolidated sediments are found across the top of the dome, uplifted but not fully breached by the salt intrusion and its overlying residual caprock. The active faults inherent in the caprock extend upward as the salt continues to intrude, deforming these overlying sediments, all the way to the surface.

Holocene Stage: The Pleistocene sands around the dome are overlain off the dome by Beaumont marine clay and mud deposited in the last 5000 yrs, during which time sea level rose some 450 ft as the earth's continental icecaps melted, leaving only the ice cover in Greenland and Antarctica. This clay was deposited in the marsh as a soft, highly-organic black gumbo. It includes peat and algal sapropels or greasy layers formed by nutrient blooms in the bays. Water content in these unconsolidated sediments is still as high as 70%. This clay is the seal for the oil accumulation in the caprock at Spindletop in Beaumont, which produced a billion barrels of black oil. Along with these Holocene clays, peats and algal sapropels are included in minor river silts and beach sands; they dip toward the Gulf at about 10 feet per mile.

At Bryan Mound, there are a few thin beach sands formed on the dune ridges. The white beach sands are very fine-grained and well-sorted. This beach-ridge complex is a fan with intervening muds, gradually subsiding into the marine clay. The sands shift dramatically during hurricanes, when waves break on the south flank sea cliff of the storage site.

The active shallow faults originating in the caprock or salt shear zones have only displaced the Holocene sediments a few feet. They do not pose any apparent risk to the storage caverns by themselves, but subsidence along them could conceivably damage surface facilities and well casings, as has occurred at other domes used for storage of LPG products, e. g., Stratton Ridge, TX.

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APPENDIX B

Earthquake Potential at Bryan Mound SPR Site

APPENDIX B

APPENDIX B

EARTHQUAKE POTENTIAL AT BRYAN MOUND SPR SITE

Natural Seismicity

Bryan Mound is one of the least seismic areas of the Gulf Coast, the least seismic region in the United States. Situated on a stable portion of the North American plate, well away from the edge of the continental shelf, the minor basement seismicity felt further inland is dampened by the thick pile of unconsolidated sediments, especially the geopressured shales upon which overlying sediments float, and to a certain extent the salt.

The 1980 site characterization report [Hogan et al., 1980] discussed the extremely low seismicity of the Gulf Coast region and concluded that small earthquakes could occur during the life of the Bryan Mound facility. Such events probably would not result in any damage to SPR caverns, either from vibratory motion or ground rupture. Several examples that follow attest to this earthquake-safe environment.

An earthquake of Magnitude 3 .8 occurred south of Lake Charles, Louisiana, on 16 Oct 83, with epicenter 17 mi north of the SPR facility at West Hackberry. Even though the felt intensity reached Modified Mercalli V (MM V) near the epicenter, the earthquake was most probably not even felt at the site, as the isoseismal map shows it to be in the MM I zone [Stevenson and Agnew, 1988]. Even near the epicenter, the maximum effects were a few instances of books falling from shelves and several unsubstantiated reports of cracked plaster, but generally only rattling of doors and dishes was noted.

The 1983 Lake Charles earthquake is instructive in explaining several aspects of Gulf Coast seismicity, and also in validating the seismic environment discussed in the 1980 site characterization report. *This earthquake is representative of the predicted risk for Bryan Mound.* Most geophysicists agree that earthquakes capable of producing intensities of MM VI (slightly larger than the Lake Charles earthquake) can occur anywhere along the Gulf Coast. Most likely these events originate in deep basement faults, or in combination with more shallow growth faults. Stevenson and Agnew [1988] proposed such a mechanism for the Lake Charles earthquake, with a focal depth of 14.04 km, possibly on a down-dip extension of the Lake Arthur growth fault system. Thus, deep normal faulting within the crystalline basement may control the configuration of many shallower Gulf Coast growth fault systems.

Nicholson and Wesson [1990] have suggested a possible relationship between this earthquake and injection activities at a nearby waste-disposal well and/or oil and gas operations. Although nothing conclusive has been established, induced seismicity occurs elsewhere from such activities. A low level of seismic activity continued in the Lake Charles region following and presumably in association with the 1983 earthquake, possibly indicating aftershocks [Stevenson, 1985]. Further discussion of induced seismicity is included later in this appendix.

The largest historical earthquake (MM VI maximum intensity near epicenter) in the Gulf Coast Province occurred near Donaldsonville, LA, on 19 Oct 30 and effectively approximates the design basis earthquake for the nuclear power industry in southeast Louisiana and south Texas. The Donaldsonville event produced an estimated maximum horizontal acceleration at the surface of -0.07 g. Such acceleration would result largely from higher frequency body-wave motion and likely would be of short (less than two seconds) duration. This does not present design difficulty even for conventional structures, such as SPR surface facilities, and would be of even less concern at subsurface cavern depths in solid salt within the dome because mine openings experience no damage at localities subject to surface accelerations up to about MM VIII [Pratt et al., 1979]., which is greater than would be expected along the Gulf Coast. However, well casing situated in fault zones could be problematic during fault reactivation associated with earth temblors. Casing rupture is not uncommon in the oil industry, but the failure mode most often seen is in rock formations more competent (brittle) than Gulf Coast sediments.

The nuclear industry has further considered a repeat New Madrid event (18 1 1-12; Magnitude 8+); peak acceleration that would be experienced at the range of Bryan Mound would be much less than a repeat Donaldsonville event near its epicenter, and most probably not be felt. Also, several earthquakes have occurred with epicenters offshore in the Gulf with magnitudes between 4.5 and 5 .O The largest not associated with a known geologic structure was Magnitude 4.8. The conservative peak horizontal acceleration value of 0.1 g used by the nuclear power industry in south Louisiana is less than what is required in the design of hurricane-force wind loads, and the 0.1 g value represents an earthquake with more than a 90% probability of nonexceedance in **250** yrs **[Figure B-l, USGS].**

A data search of all historical earthquakes greater than magnitude 2.0 that have occurred within about 400 km (-250 mi) of Bryan Mound since 1960 was conducted by the National Earthquake Information Center (U. S. Geological Survey) **[Table B-l; Figure B-21.** The results confirm the very quiet seismic environment discussed above. The nearest seismic event of note in the past 33 yrs was the 7 Apr 92 surface gas explosion which occured at Brenham salt dome, some 110 mi distant. This event had sufficient energy to be felt (and heard) as far away as Galveston.

The Apr-Aug 64 swarm of earthquakes in East Texas **(Table B-l; Figure B-2)** occurred on a system of normal faults similar to down-to-the-Gulf growth faults that offset Eocene Claiborne strata. More than 70 earthquakes with magnitudes up to 4.4 were recorded near Hemphill. The anomalous nature of this swarm is shown in the large number of events during a short period, at a locale where no seismicity had been reported prior to April of that year, nor after August. An explanation in the flexure of strata caused by sediment loading in the Gulf of Mexico Basin has been advanced, but the 1964 swarm, as opposed to random seismicity, is unexplained, (Davis et al., 1989].

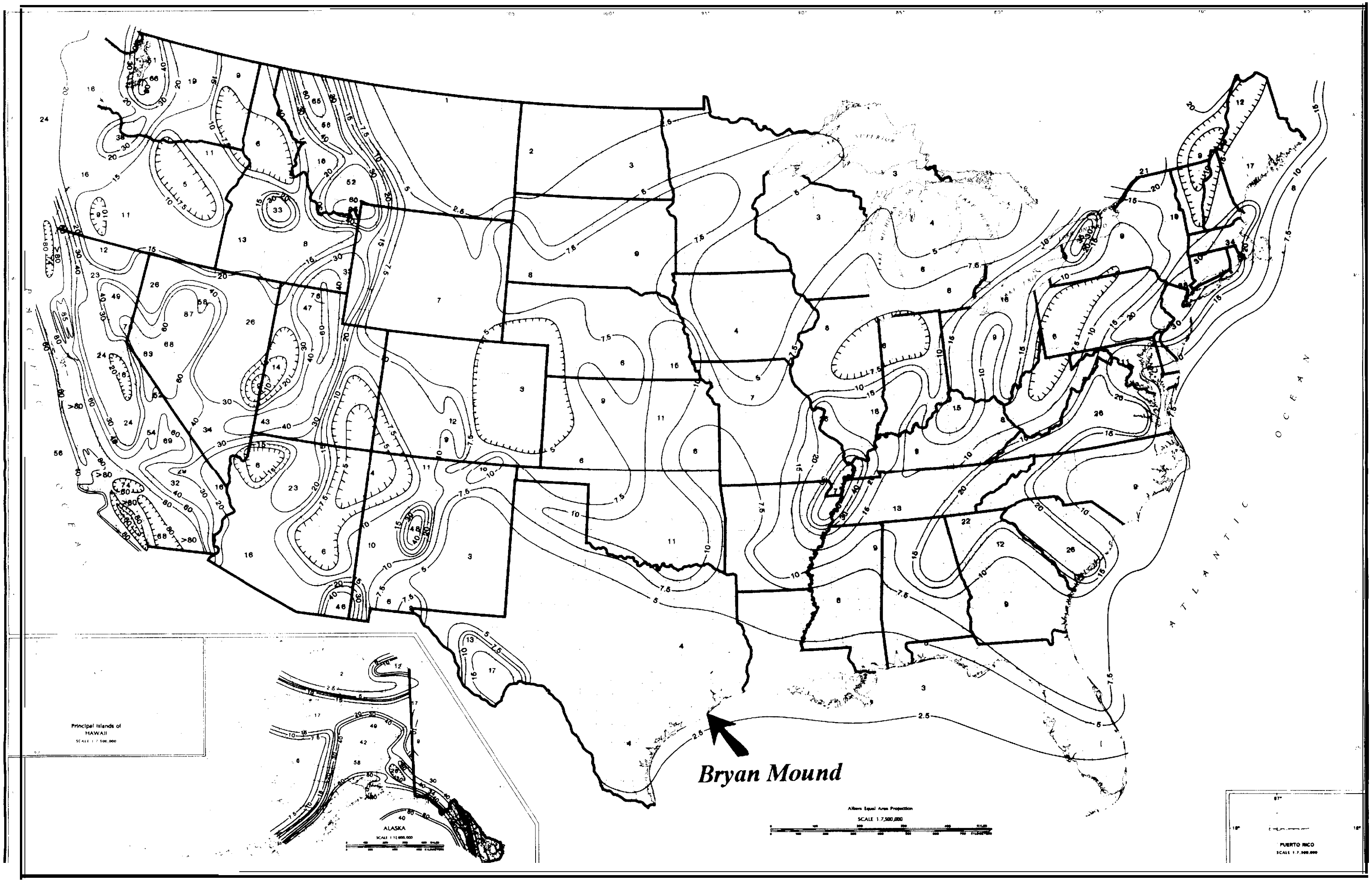

Figure B-1 Mean horizontal acceleration in %G on rock, 90% probability of non exceedance in 250 years. From Algermissen et al., 1990, U. S. Geological Survey MF-2120.

TABLE B-l SEISMIC EVENTS WITHIN 400 KM OF BRYAN MOUND; 1960-93, M 2.0-9.9 (excluding redundant reporting stations)

Date	Latitude	Longitude	Depth, km	Magnitude(*)	Range, Km.
05 Nov 63	27.800N	92.400W	33	4.8 (mb)	287
24 Apr 64	31.500	93.800	33	3.7 (mb)	299
24 Apr 64	3 1.600	93.800	33	3.7 (mb)	310
24 Apr 64	31.478	93.787	9	3.20 (Mn)	317
24 Apr 64	31.300	93.800		3.00 (mb)	299
24 Apr 64	31.300	93.800		2.60 (Mn)	299
25 Apr 64	31.300	93.800		2.60 (Mn)	299
25 Apr 64	31.300	93.800		2.90 (Mn)	299
25 Apr 64	31.300	93.800		2.90 (Mn)	299
26 Apr 64	31.300	93.800		2.70 (Mn)	299
26 Apr 64	31.550	93.780	5+	3.3 (mb)	324
27 Apr 64	31.300	93.800		3.20 (mb)	299
28 Apr 64	31.500	93.800		3.10 (mb)	318
28 Apr 64	31.500	93.800	33	3.4 (mb)	299
28 Apr 64	31.200	93.900	33	4.4 (mb)	265
30 Apr 64	3 1.200	94.000		3.00 (mb)	280
02 May 64	31.300	93.800		3.20 (mb)	299
07 May 64	31.500	93.800		3.20 (Mn)	318
02 Jun64	31.300	94.000		4.2 (mb)	290
03 Jun64	31.300	94.000	30	4.2 (mb)	290
03 Jun 64	31.000	94.000		3.60 (mb)	261
16 Aug 64	31.400	93.800		3.00(mb)	309
19 Aug 64	3 1 .000	93.800		2.70 (Mn)	299
24 Mar 66	30.000	94.000		3.00 (mb)	174
04 Oct 67	27.000	94.000		3.20	252
03 Feb 70	3 1 .000	97.000		3.80 (mb)	277
25 Dec 73	29.000	98.300		3.80 (mb)	288
13 Feb 81	30.000	91.800		3.75	362
18 Feb 81	28.230	91.360	10	3.00	396
09 Jun 81	32.142	94.399	5+	3.00 (Mn)	352
06 Nov 81	32.021	95.262	5+	3.20 (Mn)	335
28 Mar 82	29.849	98.465	5+	3.00 (Mn)	348
23 Jul 83	28.743	98.131	5+	3.40 (Mrl)	306
16 Oct 83	30.243	93.393	5+	3.40 (Mn)	207
03 Mar 84	28.852	98.461	5+	3.80 (Mn)	337
08 Aug 84	29.133	98.362	5+	3.00 (Mn)	327
20 Jul 91	28.908	98.042	10+	3.60 (Mn)	296
07 Apr 92	30.100	96.500	0+	2.30 (Mu)	189
10 Aug 92	29.000	98.500	5+	2.80 (Mn)	340
09 Apr 93	28.809	98.178	5+	4.30 (Mn)	310
16 May 93	28.810	98.170	5+	3.00 (Mn)	309

*(mb) = body-wave magnitude; Gutenberg and Richter [1956]; (Mn) = Nuttli magnitude; Nuttli [1973]
(+) = depth constrained by geophysicist

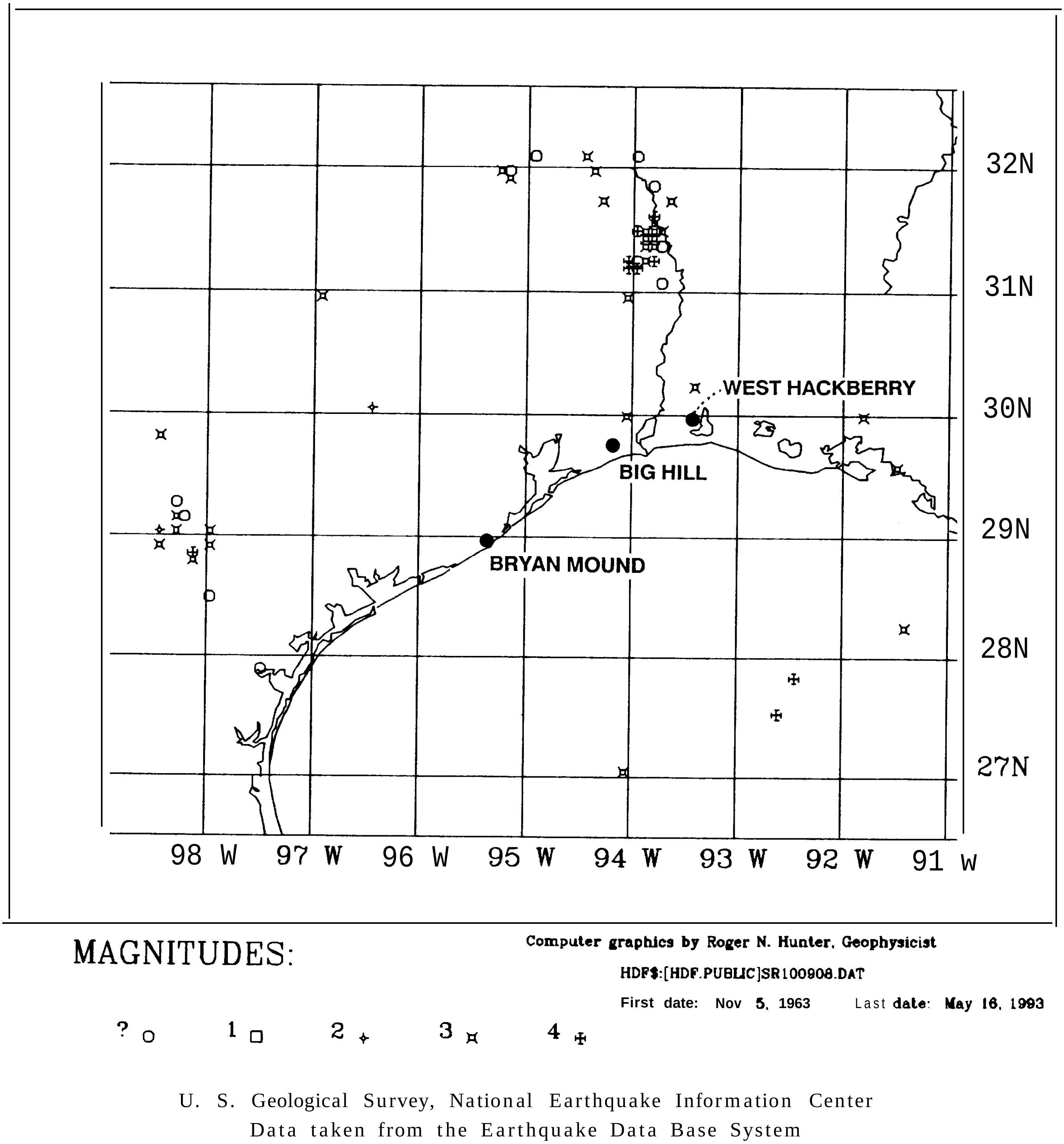

Figure B-2 Historical seismic events, 05 **Nov 63 -** 16 May 93, within 400 km radius of Bryan Mound. Magnitudes greater than 2.0 plotted; refer to **Table B-l** for listing of individual events.

Induced Seismicity

A small possibility exists for inducing earthquake activity as a result of injecting brine into metastable formations at depth. Although this phenomena had been documented at several locations prior to the 1980 characterization report, the more widespread threat has become apparent and questioned by several regulatory agencies. In West Texas, the largest earthquake induced by well injection occurred on 16 Jun 78, and had a magnitude of 4.8, which cracked plaster and windows in Snyder and neighboring towns [Davis, et al., 1989]. Because well injection does not appear to present environmental risks at Bryan Mound, it is not treated in particular detail in this update.

The effect may be to trigger rather than to cause seismicity, through the mechanism of altering the in situ stress field. Thus, the hazard from fluid injection is not that it can generate sufficient strain energy for release in earthquakes, but that it can locally reduce the effective frictional strength of faults and thus trigger earthquakes where the state of stress and the accumulated strain energy are metastable as a result of natural geologic and tectonic processes. In those cases where injection-induced seismicity was established, pore pressure increases have been the perturbation that triggered the earthquake [Nicholson and Wesson, 1990].

Where the transmissivity and storativity is low in the injection horizon, the more confined the "pressure bulb" will be around the bottom of the well and the more likely that high pore fluid pressures will occur, increasing the concern for earthquake inducement. Thus the lower the injection pressure is, the less likely the chance of triggering seismicity becomes. Ideally, in situ estimates of transmissivity and storativity should be made at the time of well completion, and used in evaluating the hydrologic environment, and the elastic constants of the reservoir formation. Once baseline conditions are established in operating wells, any increases in apparent transmissivity should be suspect as possible evidence for the opening of fractures or the occurrence of faulting.

At Bryan Mound it is not known with certainty what the frictional stress condition is on nearby growth faults. In other locations that experienced induced seismicity as a result of injection activity, the theoretical threshold for frictional sliding along favorably oriented preexisting fractures, as indicated by the Mohr-Coulomb failure criterion, was exceeded. To date there has not been any indication that injection into brine disposal wells near Bryan Mound would provide a trigger mechanism for any faults. But neither has there been large-scale introduction of brine since the brine pipeline to the Gulf was completed, thus a small amount of uncertainty remains.

The closest major growth fault to Bryan Mound that is active is the Vicksburg Flexure, approximately 10 mi to the northwest. Its rapid down-to-the-coast growth can be documented by pavement breaks along the Gulf Freeway between Houston and Galvelston having up to 5 A of displacement. However, it is aseismic, apparently because it soles out in the geopressured Vicksburg-Jackson shale, The location of the flexure coincides with the downdip or distal edge of Frio deepwater or turbidite sands. [Etter, 198 1].

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APPENDIX C

Index of Bryan Mound Well Data Used in Construction of Contour Maps and Sections

<u>Part 1</u>, p. C-2 thru C-4: listing of individual wells (on Figure 1, well location map), and origin

<u>Part 2</u>, p. C-5 thru C-24: listing of stratigraphic marker horizons by depth, as determined from well logs

NOTE: stratigraphic correlation symbols are summarized on Table 1, Appendix A, p. A-5

APPENDIX C

Part 1 List of Wells used in Maps and Cross Sections

0102-3004 are Freeport Sulphur Company wells, except those marked with asterisk are DOE/SPR Cavern Wells; 5001-5050 are Hooker Chemical Company sulphur wells; 60016052 are wells D-l through D-52 (in sequence) from Hogan et al. (1980).

0102	0440	0556	0676	0956
0113	0445	0557	0679	0975
0117	0449	0558	0687	1005
0120	0467	0560	0697	1001
0124	0469	0562	0699	1012
0126	0476	0566	0700	1013
0134	0481	0567	0702	1014
0140	0482	0568	0705	1015
0158	0492	0570	0709	1017
0162	0494	0573	0717	1019
0180	0496	0575	0718	101A*
0186	0500	0576	0719	101C*
0190	0501	0579	0727	1021
0197	0502	0580	0780	1022
0200	0503	0587	0783	1027
0204	0504	0588	0784	102B*
0211	0508	0593	0793	102C*
0265	0509	0599	0797	1031
0305	0510	0602	0804	1032
0309	0512	0603	0806	1033
0311	0513	0604	0809	103B*
0316	0514	0605	0813	103C*
0317	0515	0606	0814	1040
0331	0518	0607	0815	1044
0343	0522	0609	0818	1047
0350	0523	0610	0820	104A*
0354	0526	0626	0827	104B*
0356	0527	0637	0832	104C*
0368	0528	0638	0838	1050
0369	0529	0639	0848	1051
0371	0530	064 1	0849	1052
0374	0534	0642	0891	1056
0389	0541	0643	0895	1057
0398	0544	0652	0907	1058
0407	0546	0653	0914	1059
0421	0548	0659	0917	105B*
0422	0551	0662	0920	105C*
0433	0552	0671	0929	1060
0437	0553	0674	0950	1062

1063	1203	1356	1470	1575
1066	1208	1357	1472	1576
1068	1209	1358	1475	1577
1069	1210	1360	1483	1580
106A*	1212	1364	1484	1581
106B*	1213	1367	1491	1582
106C*	1216	1369	1495	15583
1072	1223	1377	1496	1584
1077	1224	1379	1498	1586
1078	1225	1381	1500	1589
107A*	1226	1383	1502	1591
107B*	1227	1386	1504	1592
107C*	1240	1387	1505	1593
1085	1242	1393	1506	1594
1086	1246	1394	1507	1595
1089	1253	1395	1508	1596
108A*	1258	1399	1509	1598
108B*	1262	1402	1511	1602
108C*	1264	1403	1512	1604
1090	1268	1406	1520	1605
1097	1272	1411	1525	1607
109A*	1273	1412	1528	1608
109B*	1276	1421	1530	1610
109C*	1278	1422	1535	1612
1100	1280	1423	15536	1617
1107	1282	1424	1538	11618
1109	1283	1428	1539	1619
110A*	1287	1429	1542	1620
110B*	1288	1434	1544	1622
110C*	1292	1437	1545	1623
1111	1296	1441	1549	1624
1113	1297	1442	1550	1626
111A*	1301	1445	1552	1628
111B*	1306	1446	1553	1630
112A*	1308	1447	1554	1631
112C*	1310	1448	1555	1632
113A*	1316	1449	1556	1700
113B*	1320	1450	1557	1703
114A*	1327	1452	1558	1709
114B*	1332	1453	1559	1712
115A*	1335	14556	1560	1720
115B*	1343	1459	1562	1721
116A*	1350	1464	1565	1725
116B*	1351	1468	1567	1726
1201	1352	1469	1570	1729

1733	1913	2194	5043	6039
1735	1922	2202	5044	6040
1737	1929	2213	5045	6041
1742	1931	2214	5046	6042
1743	1934	2242	5047	6043
1744	1936	2252	5048	6044
1746	1939	2618	5049	6045
1751	1940	3002	5050	6046
1758	1942	3003	6001	6047
1761	1959	3004	6002	6048
1770	1960	5001	6003	6049
1778	1973	5005	6004	6050
1781	1977	5006	6005	6051
1791	1978	5012	6006	6052
1792	1988	5013	6007	DOW1
1794	1994	5013	6008	DOW2
1801	2000	5014	6009	DOW3
1806	2005	5015	6010	DOW4
1809	2010	5016	6011	DOW5
1813	2021	5017	6012	FEL2
1814	2023	5018	6013	
1817	2029	5019	6014	**Off Map**
1822	2031	5020	6015	AMER
1823	2035	5021	6016	BD-1
1827	2043	5022	6017	BD1A
1838	2046	5023	6018	BD2A
1840	2062	5024	6019	BD2B
1841	2074	5025	6020	BD3A
1842	2078	5026	6021	BD3B
1848	2087	5027	6022	BHP1
1849	2096	5028	6023	DWFE
1850	2105	5029	6024	DWFR
1853	2118	5030	5025	RE1A
1854	2123	5031	6026	RE2A
1855	2124	5032	6027	RE4A
1866	2125	5033	6028	RE4B
1873	2127	5034	6029	RE4C
1876	2129	5035	6030	RE5A
1877	2130	5036	6031	RE5B
1885	2131	5037	6032	RE5C
1891	2140	5038	6034	
1898	2145	5039	6035	
1902	2157	5040	6036	
1906	2172	5041	6037	
1912	2186	5042	6038	

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0102	0113	0117	0120	0124	0126	0134	0140
MO								
LS								
CR	764	835	782	862	789	749	819	810
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	765	836	783	863	790	750	820	811

WELL NAME

SYMBOL	0158	0162	0180	0186	0190	0197	0200	0204
MO								
LS								
CR	771	791	712	991	913	923	864	962
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	772	792	713	992	914	924	865	963

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	0211	0235	0305	0309	0311	0316	0317	0331
MO								
LS								
CR	900	898	904	772	1002	806	816	860
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	901	899	905	773	1003	807	817	861

WELL NAME

SYMBOL	0343	0350	0354	0356	0368	0369	0371	0374
MO								
LS								
CR	1028		931	904	999	815	845	987
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1029	10000	932	905	1000	816	846	988

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0389	0398	0407	0421	0422	0433	0437	0440
MO								
LS								
CR	1038	987	1217	1022	826	820	816	967
PL								
MI								
TS			1279					
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1039	988	10000	1023	827	821	817	968

SYMBOL	0445	0449	0467	0469	0476	0481	0482	0492
MO								
LS								
CR	780	792	789		1010	824	847	728
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	781	793	790	10000	1011	825	848	729

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0494	0496	0500	0501	0502	0503	0504	0508
MO								
LS								
CR	921	859	850	757	712	722	705	820
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	922	860	851	758	713	723	706	821

SYMBOL	0509	0510	0512	0513	0514	0515	0518	0522
MO								
LS								
CR	837	775	743	722	716	736	742	709
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	838	776	744	723	717	737	743	710

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0523	0526	0527	0528	0529	0530	0534	0541
				WELL NAME				
MO								
LS								
CR	717	746	715	1145	753	732	692	740
PL								
MI								
TS				1203				
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	718	747	716	10000	754	733	693	741

SYMBOL	0544	0546	0548	0551	0552	0553	0556	0557
				WELL NAME				
MO								
LS								
CR	1134	760	718	739	727	721	736	919
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1135	761	719	740	728	722	737	920

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0558	0560	0562	0566	0567	0568	0570	0573
				WELL NAME				
MO								
LS								
CR	750	704	745	726	706	720	745	695
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	751	705	746	727	707	721	746	696

SYMBOL	0575	0576	0579	0580	0587	0588	0593	0599
				WELL NAME				
MO								
LS								
CR	1100	1100	1191	944	1073		1319	1119
PL								
MI								
TS		1141					1415	1187
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1101	10000	1192	945	1074	1650	10000	10000

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0602	0603	0604	0605	0606	0607	0609	0610
	WELL NAME							
MO								
LS								
CR	1045	1000	1097	714	1066	1040	816	799
PL								
MI								
TS		1114	1128		1101			
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1046	10000	10000	715	10000	1041	817	800

SYMBOL	0626	0637	0638	0639	0641	0642	0643	0652
	WELL NAME							
MO								
LS								
CR	718	779	699	873	789	747	701	997
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	719	780	700	874	790	748	702	998

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	0653	0659	0662	0671	0674	0676	0679	0687
	WELL NAME							
MO								
LS								
CR	701	800	717	691	979	704	764	1009
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	702	801	718	692	980	705	765	1010

SYMBOL	0697	0699	0700	0702	0703	0705	0709	0717
	WELL NAME							
MO								
LS								
CR	699	714	828	907	783	770	800	878
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	700	715	829	908	784	771	801	879

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

	WELL NAME							
SYMBOL	0718	0719	0727	0780	0783	0784	0793	0797
MO								
LS								
CR	882	892	938	784	1066	1014	894	1011
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	883	893	939	785	1067	1015	895	1012

	WELL NAME							
SYMBOL	0804	0806	0809	0812	0814	0815	0818	0820
MO								
LS								
CR	814	1133	950	1215	914	1162	865	840
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	815	1134	951	1216	915	1163	866	841

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

	WELL NAME							
SYMBOL	0827	0828	0832	0838	0848	0849	0891	0895
MO								
LS								
CR	1008	818	987	832	790	777	758	1159
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1009	819	988	833	791	778	759	1160

	WELL NAME							
SYMBOL	0907	0914	0917	0920	0929	0950	0956	0975
MO								
LS								
CR	863	689	739	824	916	885	808	806
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	864	690	740	825	917	886	809	807

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1005	1011	1012	1013	1014	1015	1017	1019
MO								
LS								
CR	1019	1116	1070	1015	1039	1099	957	891
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1020	1117	1071	1016	1040	1100	958	892

WELL NAME

SYMBOL	101A	101B	101C	1021	1022	1027	102B	102C	1031
MO	400								
LS	670								
CR	712			961	1099	1131		806	1054
PL									
MI									
TS	1056							1062	
BS									
TC	2020						2030	2000	
Al	2460		2970						
A2	2890		3210						
A3	3070		3490						
A4	3360		4205						
BC	4170						4340	4350	
S1	2190	3050	3670						
s2									
s3									
S11	2460		2970						
s12	3360		4205						
B									
AB									
RL									
DR									
TD	4506	4493		962	1100	1132	4496	4487	1055

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	1032	1033	103B	103C	1040	1044	1047	104A
MO								360
LS								680
CR	953	870	830		1246	1068	1074	
PL								
MI								
TS			1058					
BS								
TC			3150					2850
BC			4150					4180
S1								3068
s2								3300
S3								
A3			3370	3480				
A4			3585	3820				
B								
AB								
RL								
DR								
P								
F								
TD	954	871	4515	4490	1247	1069	1075	4531

WELL NAME

SYMBOL	104B	104C	1050	1051	1052	1056	1057	1058
MO								
LS								
CR	724	732	1133	1301	1003	1062	985	904
PL								
MI								
TS	1048	1049						
BS								
TC								
BC								
S1								
s2								
s3								
AN		4034						
HR								
B								
AB								
RL								
DR								
P								
F								
TD	4515	4501	1134	1302	1004	1063	986	905

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	1059	105B	105C	1060	1062	1063	1066	1068
MO		360						
LS		690						
CR	1541	751	734	1098	1296	903	1236	1235
PL								
MI								
TS		1050	1053					
BS								
TC		2760						
BC		4199						
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1542	4480	4484	1099	1297	904	1237	1236

WELL NAME

SYMBOL	1069	106A	106B	106C	1072	1077	1078	107A
MO		335						490
LS		660						690
CR		697	698	696	1213	1002	1124	708
PL								
MI								
TS		1051	1052	1050				1048
BS								
TC			2100					
BC			4219					
S1								2660
s2		3060		3240				
s3		3490		3440				
S10		2750	3020	3670				
AN				2358				
HR								
Al5		2800						
RL								
DR								
P								
F								
TD	1750	4493	4542	4492	1214	1003	1125	4473

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	107B	107C	1085	1086	1089	108A	108B	108C
MO								
LS								
CR	728	728	1310			721	740	713
PL								
MI								
TS	1057	1053				1055	1060	1054
BS								
TC	3260							3260
BC	4120							4150
S1	3023	3346				2315	2104	1450
S2		3650				2663	2270	1745
s3						3570	2670	
s13						1640	2100	1450
S14								
AN								
HR								
RL								
DR								
P								
F								
TD	4506	4474	1311	10000	10000	4485	4567	4487

WELL NAME

SYMBOL	1090	1097	109A	109B	109C	1100	1107	1109
MO			390					
LS								
CR	1208	1317	690	700	698	1342	992	1132
PL								
MI								
TS			1055	1056	1053			
BS								
TC				2940				
BC				4200				
S1								
s2								
s3								
s14			2040		3250			
AN								
HR								
AB								
RL								
DR								
P								
F								
TD	1209	1318	4501	4524	4497	1343	993	1133

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

	WELL NAME							
SYMBOL	110A	110B	110C	1111	1113	111A	111B	112A
MO	380					415		315
LS	670					835		660
CR	730	732	729	952	957	916		
PL								
MI								
TS	1058	1059	1056			1071	1072	
BS								
TC	2110					3130		
BC	4250					4170		
S1	2185		2103					
s2	2399		2868					
s3	3642	3720	3665					
AN	3740		3730					
HR								
B								
AB								
RL								
DR								
P								
TD F	4488	4493	4480	953	958	4494	4503	4489

	WELL NAME							
SYMBOL	112C	113A	113B	114A	114B	115A	115B	116A
MO						450		430
LS								
CR	719							
PL								
MI								
TS	1051							
BS								
TC	2930	2130		2130		2150		2150
BC	4180	4220		4180		4140		4270
S1		2990	3463					
s2								
s3								
K1				3050	3130			
K2				3150	3230			
B								
AB								
RL								
DR								
P								
F								
TD	4483	10000	10000	10000	10000	10000	10000	10000

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

	WELL NAME							
SYMBOL	116B	1201	1203	1208	1209	1210	1212	1213
MO								
LS								
CR		1021	822	1342	1220	915	1135	916
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	1022	823	1343	1221	916	1136	917

	WELL NAME							
SYMBOL	1216	1223	1224	1225	1226	1227	1240	1242
MO								
LS								
CR	1089	1070	898	1398	904	1337	1414	1046
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1090	1071	899	1399	905	1338	1415	1047

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1246	1253	1258	1262	1264	1268	1272	1273
MO								
LS								
CR	690	1077	1050	1206	1250	1151	1253	696
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	691	1078	1051	1207	1251	1152	1254	697

SYMBOL	1276	1278	1280	1282	1283	1287	1288	1292
MO								
LS								
CR		1338	905		1125	820	1107	1323
PL								
MI								
TS		1369						
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	10000	906	10000	1126	821	1108	1324

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1296	1297	1301	1306	1308	1310	1316	1320
MO								
LS								
CR	702	911	1022	789		965	814	1053
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	703	912	1023	790	10000	966	815	1054

SYMBOL	1327	1332	1335	1343	1350	1351	1352	1356
MO								
LS								
CR	918	1130	1172			1095	1291	967
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	919	1131	1173	10000	10000	1096	1292	968

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	1357	1358	1360	1364	1367	1369	1377	1379
MO								
LS								
CR	1119	979		878	1344	990	915	1357
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1120	980	10000	879	1345	991	916	1358

WELL NAME

SYMBOL	1381	1383	1386	1387	1393	1394	1 95	1399
MO								
LS								
CR	897	764	904	907		1236		936
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	898	765	905	908	10000	1237	10000	937

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	1402	1403	1406	1411	1412	1421	1422	1423
MO								
LS								
CR	918		1278	1050	1103	1102	927	835
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	919	10000	1279	1051	1104	1103	928	836

WELL NAME

SYMBOL	1424	1428	1429	1434	1437	1441	1442	1445
MO								
LS								
CR		1073	927	1141		1480	1180	1035
PL								
MI								
TS				1200				
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	1074	928	10000	10000	1481	1181	1036

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1446	1447	1448	1449	1450	1452	1453	1456
MO								
LS								
CR	1006	929	968	1403	1030	1332	876	
PL								
MI								
TS						1336		
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1007	930	969	1404	1031	10000	877	10000

SYMBOL	1459	1464	1468	1469	1470	1472	1475	1483
MO								
LS								
CR	1075	900	1143	807	1220	841	1018	959
PL								
MI								
TS			1153					
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1076	901	10000	808	1221	842	1019	960

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1484	1491	1495	1496	1498	1500	1502	1504
MO								
LS								
CR	907	1033	804	866	788	682	700	726
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	908	1034	805	867	789	683	701	727

SYMBOL	1505	1506	1507	1508	1509	1511	1512	1520
MO								
LS								
CR	692	703	728	883	700	697	702	806
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	693	7 4	729	884	701	698	703	807

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

	WELL NAME							
SYMBOL	1525	1528	1530	1535	1536	1538	1539	1542
MO								
LS								
CR	785	936	743	719	790	1008	1364	1057
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	786	937	744	720	791	1009	1365	1058

	WELL NAME							
SYMBOL	1544	1545	1549	1550	1552	1553	1554	1555
MO								
LS								
CR	975	1223	1288	814	1037	1109	1301	1020
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	976	1224	1289	815	1038	1110	1302	1021

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

	WELL NAME							
SYMBOL	1556	1557	1558	1559	1560	1562	1565	1567
MO								
LS								
CR	1112	1045	1423	716	995	712	696	703
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1113	1046	1424	717	996	713	697	704

	WELL NAME							
SYMBOL	1570	1575	1576	1577	1580	1581	1582	1583
MO								
LS								
CR	702	927	737	784	890	736	720	707
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	703	928	738	785	891	737	721	708

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	WELL NAME 1584	1586	1589	1591	1592	1593	1594	1595
MO								
LS								
CR	1447	733		874		819	858	749
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1448	734	10000	875	1566	820	859	750

SYMBOL	WELL NAME 1596	1598	1602	1604	1605	1607	1608	1610
MO								
LS								
CR	1380	749	777	864	1370	872	1308	958
PL								
MI								
TS							1312	
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1381	750	778	865	1371	873	10000	959

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	WELL NAME 1612	1617	1618	1619	1620	1622	1623	1624
MO								
LS								
CR	896	1183	1251	1461		1402		1219
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	897	1184	1252	1462	1305	1403	1518	1220

SYMBOL	WELL NAME 1626	1628	1630	1631	1632	1700	1703	1709
MO								
LS								
CR	785			700	1332	843	1088	876
PL								
MI								
TS					1336		1098	
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	786	1800	1692	701	10000	844	10000	877

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1712	1720	1721	1725	1726	1729	1733	1735
MO								
LS								
CR		884	858	889	953	803	1040	
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	885	859	890	954	804	1041	10000

SYMBOL	1737	1742	1743	1744	1746	1751	1758	1761
MO								
LS								
CR	1127	861	1127	1180	818	1155	1145	923
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1128	862	1128	1181	819	1156	1146	924

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1770	17'78	1'781	1791	1792	1794	1801	1806
MO								
LS								
CR	695	707	771	880	968		1176	701
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	696	708	772	881	969	10000	1177	702

SYMBOL	1809	1813	1814	1817	1822	1823	1827	1838
MO								
LS								
CR		706	866				828	1028
PL								
MI								
TS								1080
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	707	867	10000	10000	10000	829	10000

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1840	1841	1842	1848	1849	1850	1853	1854
	WELL NAME							
MO								
LS								
CR	1436	894	835	918	880	756		
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1437	895	836	919	881	757	1607	1456

SYMBOL	1855	1866	1873	1876	1877	1885	1891	1898
	WELL NAME							
MO								
LS								
CR	760	1270	771	976	785	880	854	1079
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	761	1271	772	977	786	881	855	1080

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1902	1906	1912	1913	1922	1929	1931	1934
	WELL NAME							
MO								
LS								
CR	724	1204	803	1209	1012	980	990	
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	725	1205	804	1210	1013	981	991	10000

SYMBOL	1936	1939	1940	1942	1959	1960	1973	1977
	WELL NAME							
MO								
LS								
CR	998	1264	961	1115	1547	1240	1083	1146
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	999	1265	962	1116	1548	1241	1084	1147

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	1978	1988	1994	WELL NAME 2000	2005	2010	2021	2023
MO								
LS								
CR	1000	1195	911	881	1172	1052	939	811
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1001	1196	912	882	1173	1053	940	812

SYMBOL	2029	2031	2035	WELL NAME 2043	2046	2062	2074	2078
MO								
LS								
CR	913	784	925	1131	1142	963	778	1257
PL								
MI								
TS								
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	914	785	926	1132	1143	964	779	1258

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	2087	2096	2105	WELL NAME 2118	2123	2124	2125	2127
MO								
LS								
CR	882	878	800	771	976	800	1080	931
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	883	879	801	772	977	801	1081	932

SYMBOL	2129	2130	2131	WELL NAME 2140	2145	2157	2172	2186
MO								
LS								
CR	858	887		929	941	1437	985	892
PL								
MI								
TS								
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	859	888	10000	930	942	1438	986	893

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	2194	2202	2213	2214	2242	2252	2618	3002
MO								
LS								
CR	1349	1455	1293	1428	1040		899	1005
PL								
MI								
TS		1520			1092			
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	1350	10000	1294	1429	10000	10000	900	1006

SYMBOL	3003	3004	5001	5005	5006	5012	5013	5014
MO								
LS								
CR	974	932						826
PL								
MI								
TS								1053
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	975	933	10000	10000	10000	10000	10000	10000

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	5015	5016	5017	5018	5019	5020	5021	5022
MO								
LS								
CR						783		
PL								
MI								
TS						1045		
BS								
TC								
BC								
S1								
s2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	10000	10000	10000	10000	10000	10000	10000

SYMBOL	5023	5024	5025	5026	5027	5028	5029	5030
MO								
LS								
CR	936				864			
PL								
MI								
TS	1076				1062			
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	10000	10000	10000	10000	10000	10000	10000

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	5031	5032	5033	5034	5035	5036	5037	5038
MO								
LS								
CR	1285							
PL								
MI								
TS	1418							
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	10000	1000	10000	10000	10000	10000	10000

WELL NAME

SYMBOL	5039	5040	5041	5042	5043	5044	5046	5047
MO								
LS								
CR	874	947		1406				
PL								
MI								
TS	1066	1077		1500				
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	10000	10000	10000	10000	10000	10000	10000

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	5048	5049	5050	6001	6002	6003	6004	6005
MO								
LS				830		910		
CR	1014	765	1069					
PL								
MI				1880		1720		
TS	1162	1049	1108	4795				
BS				4807				
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB				2520		2220		
RL				2840		2420		
DR				3220		2855		
P				3700				
F								
TD	10000	10000	10000	10000	1372	3633	1587	1355

WELL NAME

SYMBOL	6006	6007	6008	6009	6010	6011	6012	6013
MO								
LS		840	890					
CR	1351			705				
PL								
MI		1940	2165					
TS				1043				1805
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B								
AB		2630	3520					
RL								
DR								
P								
F								
TD	1357	3680	4592	6143	4209	1955	2712	1806

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	6014	6015	6016	6017	ST- 1	ST- 2	ST- 3	6018
MO								
LS								
CR								1316
PL								
MI		1960		2544				1670
TS			5555	3900			3846	1390
BS							3851	1485
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B								
AB	2950	2870		3150				2310
RL		3500						2600
DR	2945	4080		3310				2940
P		4350		3834				3550
F								
TD	4519	4892	6031	4715	4715	3906	3935	4005

WELL NAME

SYMBOL	6019	6020	6021	6022	6023	6024	6025	6026
MO								
LS				940	650			
CR								914
PL								
MI	1880	1750	1635	2040	2190			
TS						1375	102	1090
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR			2842					
B								
AB	2450	2470	2100	3230	3540			
RL	3010	3005	2270	3570	4210			
DR	3120	3100	2470	4790	5250			
P	3300							
F								
TD	3487	3603	3014	6792	7580	1376	2500	1098

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

WELL NAME

SYMBOL	6027	6028	6029	6030	6031	6032	6033	6034
MO					490			390
LS					990			790
CR								
PL								
MI					2340	2070		2260
TS		1272			13690	5210		3200
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B					3475	2865		2415
AB					3560	3180		3120
RL					4080	3390		3490
DR					4620	3595		3660
P					5400			3850
F					9700			
TD	3107	1292	2089	2318	14029	5363	6099	4715

WELL NAME

SYMBOL	6035	6036	6037	6038	6039	6040	6041	6042
MO	415	555	440	510	410	510		
LS	810	1035	840	940	750	850		
CR								
PL								
MI	1790	2300	2300	2425	2165	2070		2060
TS			4530	16650	5166			
BS								
TC								
BC								
S1								
s2								
s3								
AN								
HR								
B		3630	2940	3710	2970	2510		2555
AB	2370	4310	3260	4350	3190	3440		3310
RL	2780	4935	3630	4620	3605			3515
DR	3190	6330	3900	5720	4010			3590
P		9420		6840	4520			
F		15705		10060				
TD	3525	17670	10000	16905	5166	4072	1355	3660

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	6043	6044	6045	6049	6050	6051	6052	AMER
				WELL NAME				
MO							450	
LS					990		920	
CR								
PL					1800		1870	1780
MI	2140	1462			2215		2340	2340
TS		3727	3854					
BS								
TC								
BC								
S1								
S2								
S3								
AN								
HR								
B					3100		3300	3620
AB	2810	2192			3620		4380	4450
RL	3240	2274			4190		5040	5070
D	3420	3716			5370		6450	6300
P	3950				5810			
F								
TD	4293	3782	10000	2054	7503	5614	6807	0000

SYMBOL	BD-1	BD1A	BD2A	BD2B	BD3A	BD3B	BHP1	DOW1
				WELL NAME				
MO								
LS						1030		
CR								707
PL	1950	2015	1870	2060		2000		
MI	2455	2570	2470	2605		2520	2310	
TS								1057
BS								
TC								2350
BC								2810
S1								
S2								
S3								
AN								
HR								
B	3990	4175	4120	4370		4240	3730	
AB	4915	5110	4780	4975		4790	4705	
RL		5475	5265	5470		5340	5165	
DR							6945	
P							7550	
F							13610	
TD	10000	10000	10000	10000	10000	10000	14000	3446

BRYAN MOUND SALT DOME
SUMMARY OF WELL LOG INTERPRETATION

SYMBOL	DOW2	DOW3	DOW4	DOW5	DWFE	DWFR	FEL1	FEL2
				WELL NAME				
MO								
LS					930	990		
CR	745		738	712				
PL								
MI					2380	2390	2220	2210
TS	1070	1104	1048	1061				
BS								
TC	1450	1520						
BC	1670	1720						
S1								
S2								
S3								
AN								
HR								
B					3770	3695		
AB					4670	4740	3170	3670
RL					5290	5210	3360	4450
DR					6260	7080	4330	
P					7040	7840		
F						11995		
TD	10000	10000	3508	3620	10000	12000	10000	10000

SYMBOL	RE1A	RE2A	RE4A	RE4B	RE4C	RE5A	RE5B	RE5C
				WELL NAME				
MO								
LS								
CR	717	742	729	728	721	692		690
PL								
MI								
TS	1057	1057	1049	1053	1051	1061		1055
BS								
TC	2354	1470	2573	2870	2562	2140		2757
BC	2817	1672		3080	3110	3280		3249
S1								
S2								
S3								
AN								
HR								
B								
AB								
RL								
DR								
P								
F								
TD	10000	10000	2574	9993	3111	10000	1057	10000

APPENDIX D

Selected Core and Thin Section Photographs

APPENDIX D

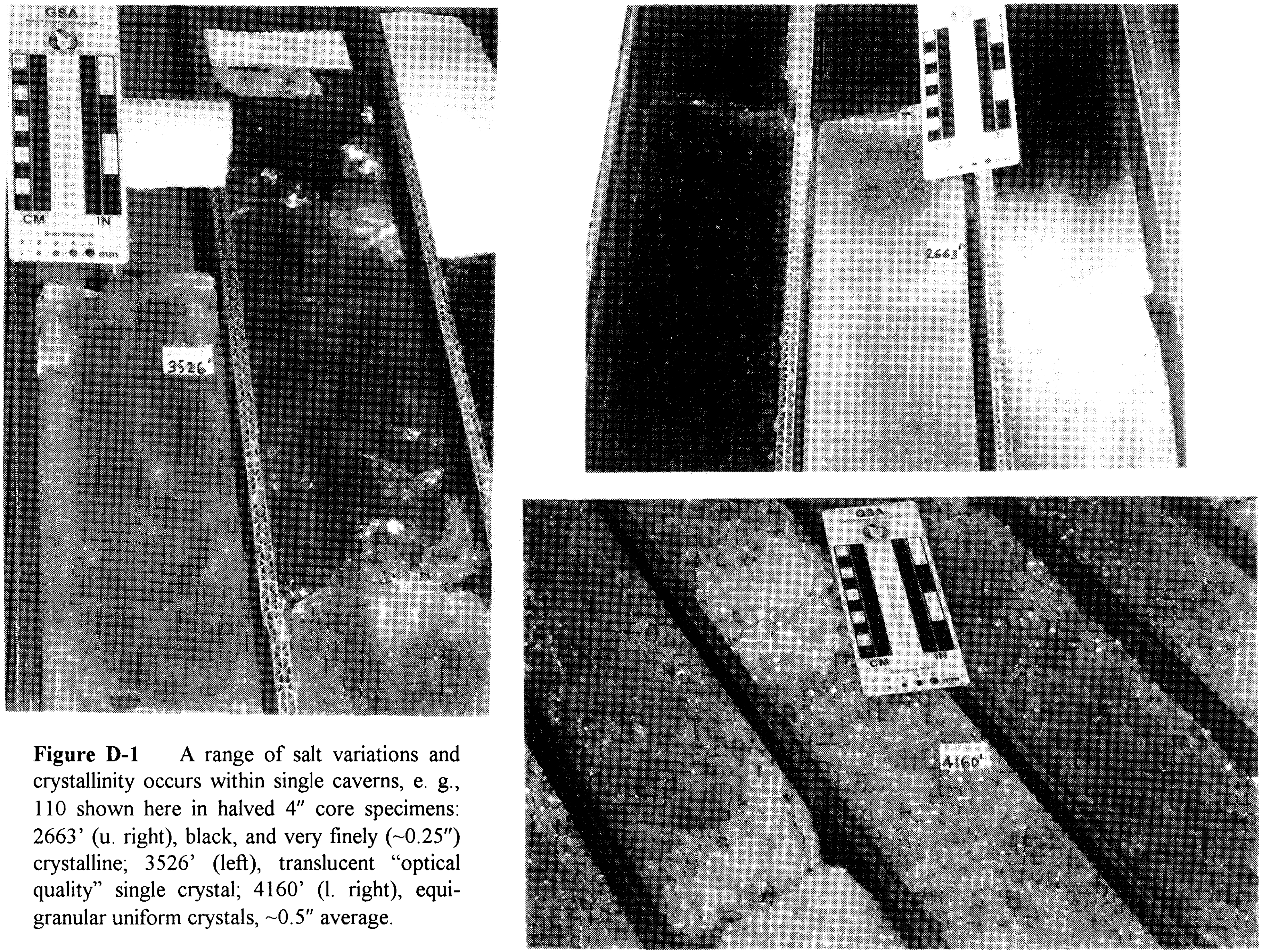

Figure D-1 A range of salt variations and crystallinity occurs within single caverns, e. g., 110 shown here in halved 4″ core specimens: 2663' (u. right), black, and very finely (~0.25″) crystalline; 3526' (left), translucent "optical quality" single crystal; 4160' (l. right), equigranular uniform crystals, ~0.5″ average.

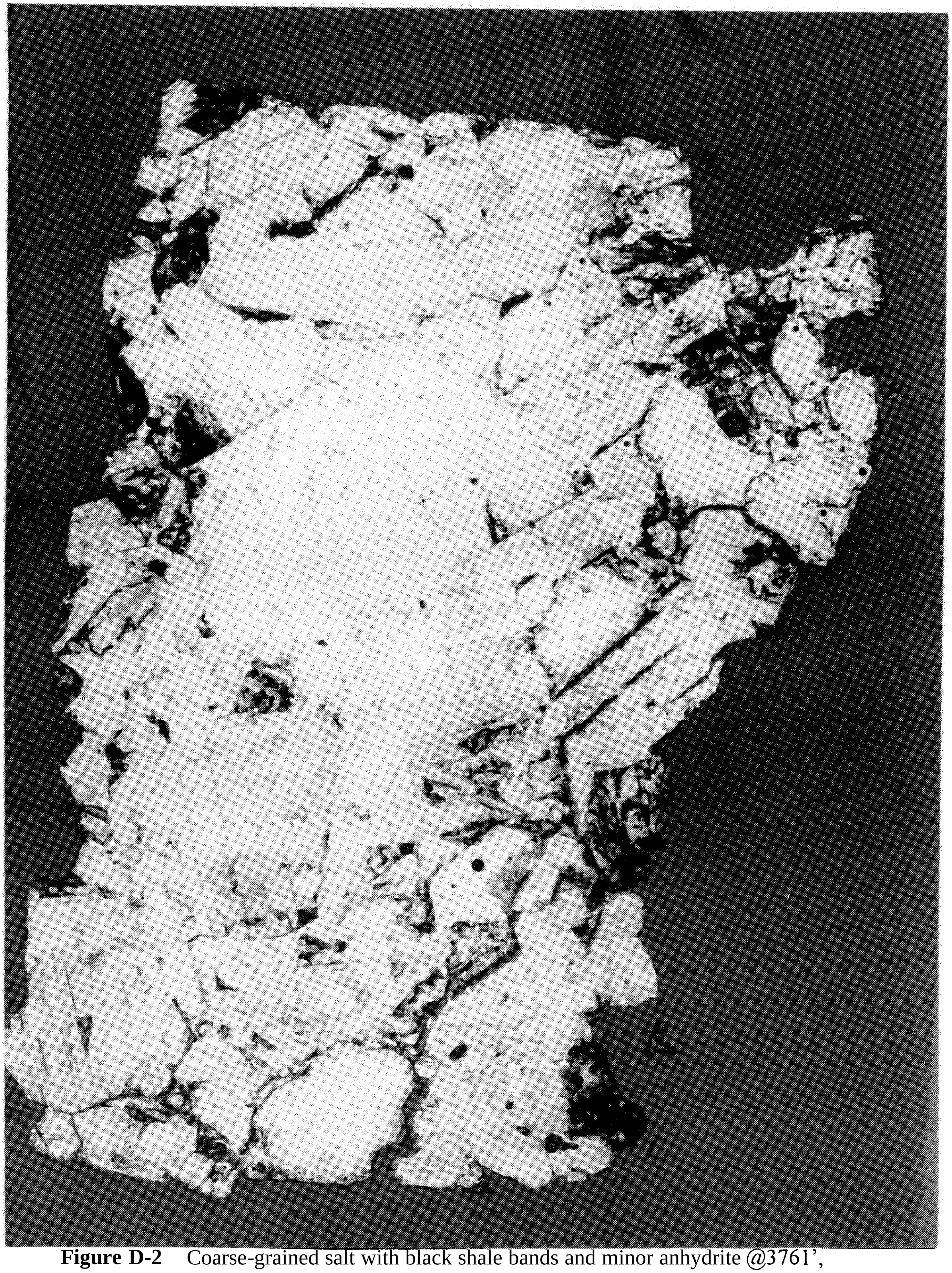

Figure D-2 Coarse-grained salt with black shale bands and minor anhydrite @3761', Cavern 11 OB. Magnification X 10.13

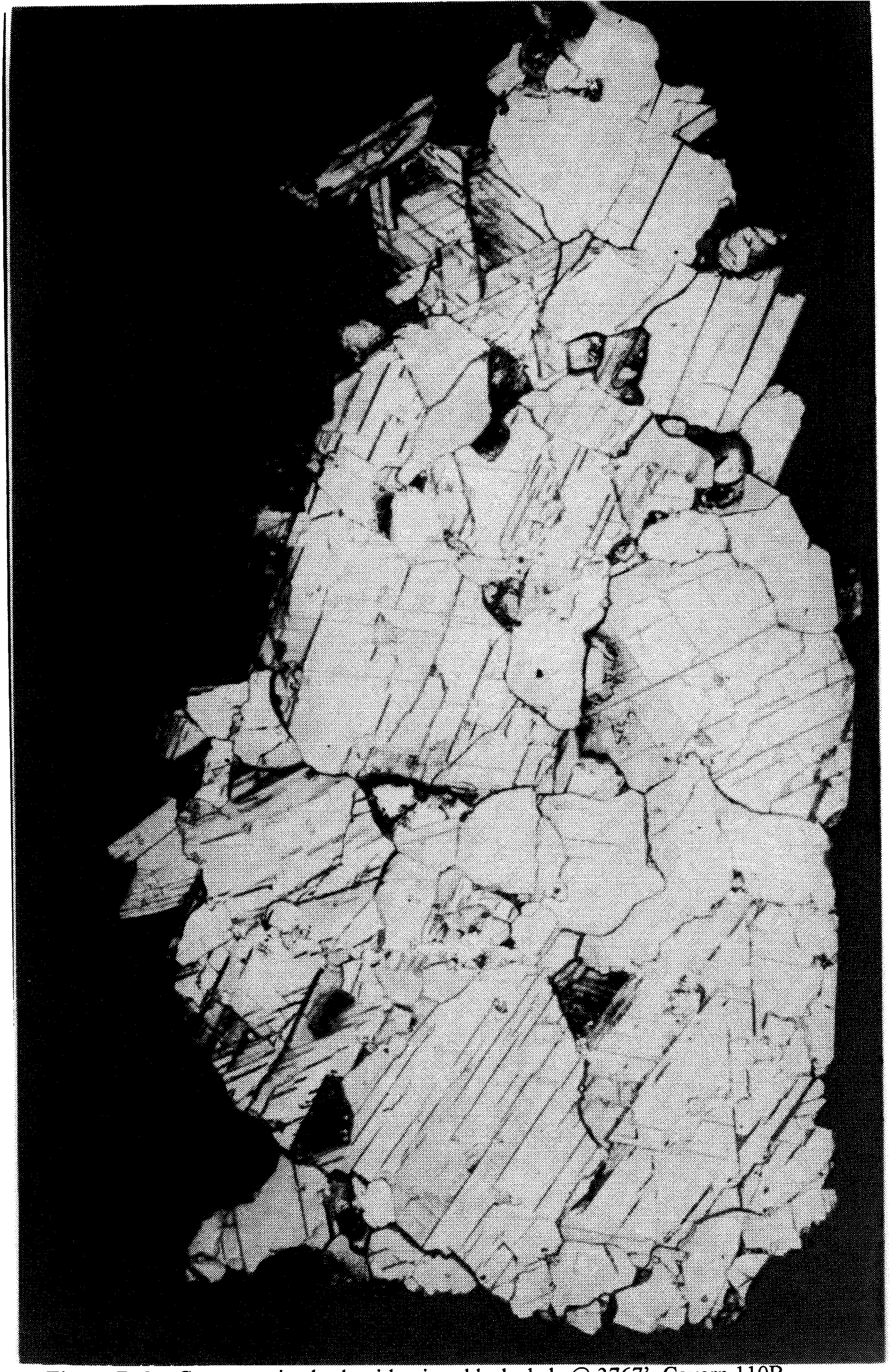

Figure D-3 Coarse-grained salt with minor black shale @ 3767', Cavern 110B.
Magnification X 9.03

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